Drag Reduction in Pipes Lined with Riblets

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Theme

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

Contents

There is a large 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[1,2,3]. 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^* is the friction velocity and ν is the kinematic viscosity. He also found that triangular grooves are among the most effective in reducing drag.

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Less is known about the effect of riblets on drag reduction in pipe flow. Nitschke[4] studied air flow 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 to 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 0.11mm riblet film while 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 11.6m. The water flowed from the head tank first through a 7.6cm (3") diameter pipe, then turned in a 15.2cm (6") 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 2.13m (7 ft.) or 84 d, 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 equation (3) below.

The two pipes that constitute the test section were in series, each equipped with 4 pressure taps at equal distances. A flowmeter was placed downstream from the test section and a gate valve, to control the flow, followed the flowmeter. Both the flowmeter and the gate valve were located far enough from the test section to avoid any backflows or any effects on the pressure measurements.

Flowrates, pressure drops and temperatures of the water were measured during the experiments. The pipes used were PVC, smooth 50.8mm (2") and 25.4mm (1") diameter and 3.05m (10 ft.) long. For technical reasons, only 1.5m were lined with film in the 25.4mm (1") case and 2.4m in the 50.8mm (2") 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

$$f = \frac{\Delta P}{\rho g}\,\frac{2g}{U^2}\,\frac{d}{L}. \qquad (1)$$

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

$$d_r = \sqrt{\frac{4A}{\pi}} \qquad (2)$$

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

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

where the Reynolds number Re=dU/v, 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 a quite good agreement with average differences of about 1 percent with a maximum difference of about 3 percent.

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 ensured that our data were repeatable. Second, it ensured 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 Figure 1. In these experiments S is fixed but S^+ varies. The data do not determine a lower limit for drag reduction, although it suggests that it must be around

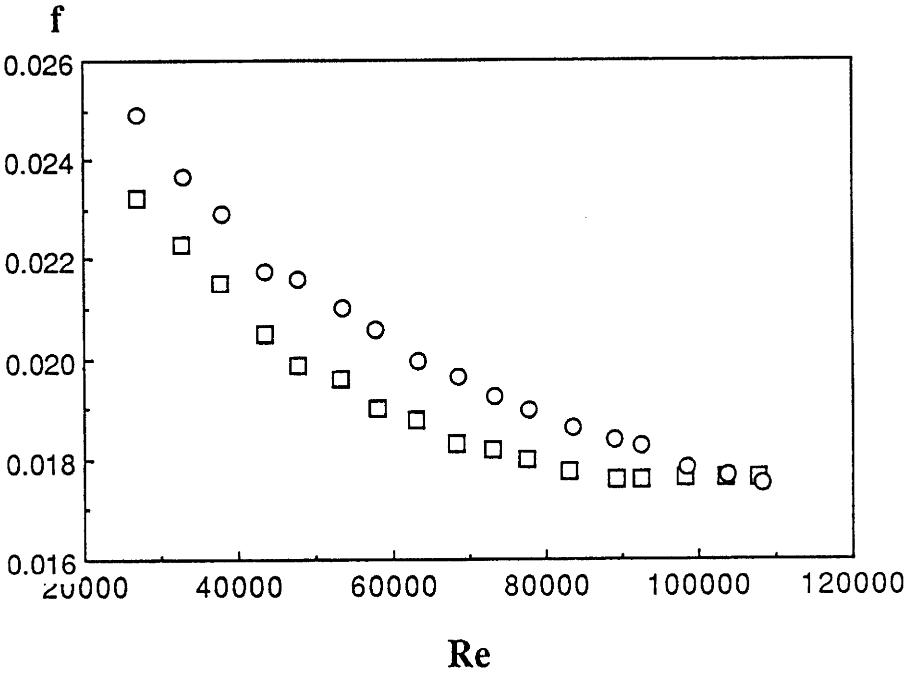

Figure 1: Comparison of the measured values of the friction factor in the section with the smooth film with the 25.4mm diameter pipe lined with riblets.

□ Riblet film

○ Smooth pipe

$S^+=3$. 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. Nearly identical results have been reported by Nitschke[4] in a study of air flow in pipes with grooved walls.

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

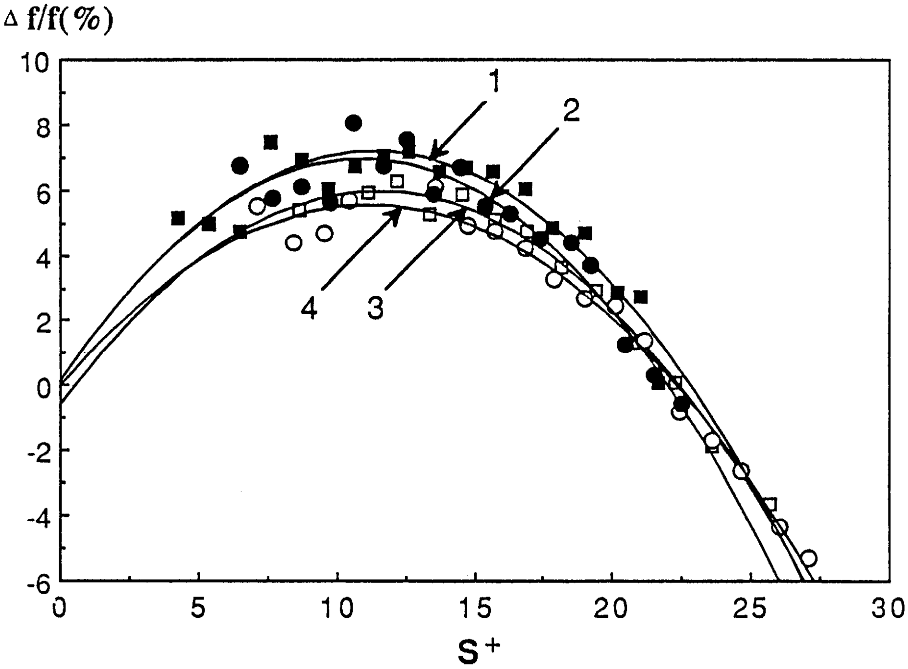

Figure 2: Percent drag reduction due to riblets:

Line 1: 25.4mm pipe lined with smooth film ●
Line 2: 50.8mm pipe lined with smooth film ■
Line 3: 25.4mm smooth unlined pipe ○
Line 4: 50.8mm smooth unlined pipe □

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

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

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

$$\lambda^2 = \overline{u_y^2} / \overline{\left(\frac{\partial u_y}{\partial z} \right)^2} \, . \qquad (5)$$

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* 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 $S^+=12\pm2$. The pocket scales do not correlate with drag reduction.

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 $\lambda=12\pm2$.

Remarkably, this λ is also near the value of S^+ which maximizes 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 $-\overline{uv}dU/dy$ peaks at $y^+\sim15$ in fully-developed pipe and channel flows[7] and that the minimum spanwise distance between sensors which is required to sense structure in turbulence is reported to be 11 wall units[8].

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