11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

FLOW AND FRICTION LOSS IN A TWO-DIMENSIONAL CHANNEL WITH ROUGH WALLS

Shiro AKAIKE[1], Ichiro NAKANE[1], Mitsumasa NEMOTO[1] and Toshimichi SAKAI[2]

[1]Kanagawa Institute of Technology, 1030 Shimo-Ogino, Atsugi 243-02, JAPAN

[2]Science University of Tokyo, 1-3 Kagurazaka, Shinjuku 162, JAPAN

ABSTRACT

Although the friction loss on a rough wall is commonly calculated from the well known formula based on the equivalent sand roughness Ks, the roughness of the flow passage, such as turbomachinery, is expressed by the arithmetic center-line average Ra. In this study, the flow and friction loss for the completely developed flow regime in the two dimensional channel with a rough wall are investigated experimentally. While there is a certain degree of the correlation between Ks and Ra for the friction loss for the completely rough regime, there is no correlation between them for the transition regime. The empirical equations for the friction loss coefficient based on the relative roughness of Ra are presented.

NOTATION

- B : roughness function
- ΔB : constant occurring in the logarithmic law
- b : height of the channel
- Cp : pressure coefficient
- M : hydraulic mean depth
- Ks : equivalent sand roughness
- p : static pressure
- Δp : pressure difference between the inlet and the measuring section in the channel
- Ra : arithmetic center-line average roughness
- Re : Reynolds number, $= \bar{u} \cdot 4M / \nu$
- u : velocity component in the x-direction
- $\bar{u}$: mean velocity in the channel
- u_{max} : maximum velocity at the middle section in the channel
- $U\tau$: friction velocity
- u^+ : dimensionless velocity, $= u/ U\tau$
- x : distance measured from the inlet of the channel
- y : distance measured from the channel wall
- y_c : distance measured from the middle section in the channel
- y^+ : dimensionless distance, $= y\, U\tau / \nu$
- w : width of the channel
- ν : kinematic viscosity
- ρ : density
- λ : pipe friction loss coefficient

INTRODUCTION

Fully developed turbulent flow in two-dimensional channel with smooth wall was previously investigated by a number of researcher and the mean characteristics of the flow in the channel were already clear(Dean, 1978). The wall of the flow passage of a turbomachinery is usually not hydraulically smooth. When the friction loss of the flow passage is calculated, it is necessary to consider the effect of the roughness of the passage wall. Although the friction loss of a rough wall is commonly calculated from the well known formula based on Ks, the roughness of the flow passage is expressed by Ra. Therefore, it is important to determine the correlation between Ks and Ra.

There exists a considerable literature on the correlation, but there are many differences between the correlations obtained from the previous studies(Akaike, 1991). We recommended the practical correlation (Ks=8 Ra) for the completely rough regime (Akaike et al. ,1992). However, many problems to be solved on the flow and the friction loss in the channel with a rough wall remain.

This study is designed to secure the flow and the friction loss in the two-dimensional channel with a rough wall. Experiments are carried out for the channels roughened by the three kinds of sand papers which are varied with the roughness Ra. The height of the channels is also varied. Friction loss, velocity distribution and the correlation between Ks and Ra are discussed. For the friction loss coefficient, the empirical equations on the functions of the relative roughness Ra/4M and the Reynolds number are obtained.

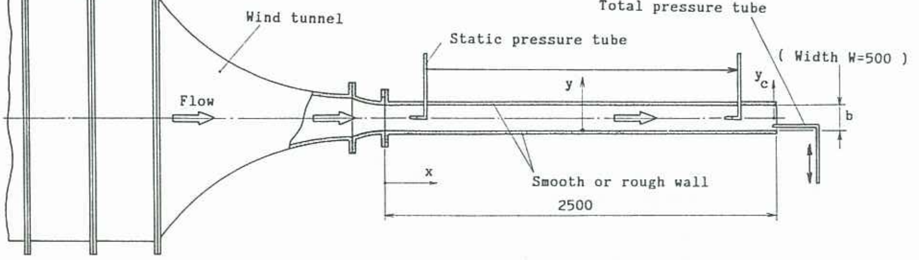

Fig. 1 Schematic diagram of equipment (unit mm)

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Figure 1 shows a schematic diagram of the two-dimensional channel using an air as working fluid, which was set downstream of the wind tunnel. The width w of the channel was 500mm and the height b was varied with 30, 40, 50mm. The aspect ratio w/b of each channel was 16.7, 12, 10, respectively.

The roughness of the channel wall was made by covering three kinds of the sand papers(#40, #80, #180), which were different from the roughness. The arithmetic center-line average Ra and the ten point height Rz of the sand papers used are shown in Table 1. Since the surfaces of the sand paper were $Rz/Ra \fallingdotseq 4$, these surfaces may reproduce a casting surface or a machined surface.

The static pressure along the channel was measured by using a static tube which was inserted at the middle section into the channel. The kinematic pressure in the channel was measured by using a total pressure tube which was inserted from the exit as shown in Fig.1. The two-dimensional flow in the channel was verified by measuring the static pressure and the velocity distribution in the width direction of the channel.

Experiments were carried out for the Reynolds number $Re \fallingdotseq (0.5 \sim 1.2) \times 10^5$ and the mean velocity $\bar{u} \fallingdotseq 15 \sim 45$m/s.

EXPERIMENTAL RESULTS AND DISCUSSION

Friction Loss of Channel

Figure 2 shows an example of the pressure distribution along the channel of b=30mm, Ra=104μm. Since the gradient of pressure distribution becomes nearly constant at $x/b \gtrsim 30$, it is likely that the flow downstream of there is completely developed.

Pressure coefficient Cp is defined as follows:

$$Cp = 2\,\Delta p \,/\, \rho\,\bar{u}^2 - 1 \qquad (1)$$

Figure 3 shows the variation of the distribution of Cp with the wall roughness. The pressure gradient becomes steeper, as the roughness of the channel wall increases. The straight lines in two figures are obtained from the experimental results by the method of least squares where the flow in the channel is fully developed. The gradient of Cp of course increases as the roughness height increases.

Pipe friction loss coefficient is determined from the gradient of the Cp-distribution. An example of the relationship between the loss coefficient λ and the Reynolds number of b=30mm is shown in Fig.4. In the figure, Prandtl-Kárman equation (2) of the friction loss coefficient for the smooth wall and the well known transition equation (3) are plotted.

$$1/\lambda^{1/2} = 2.0\log(Re \cdot \lambda^{1/2}) - 0.8 \qquad (2)$$

$$(Re \cdot \lambda^{1/2})(Ks/4M) = 200 \qquad (3)$$

The experimental coefficients for the smooth wall agree well with Eq.(2)(see Fig.10). The friction loss coefficients for the rough wall channel increases with increasing of the roughness.

Velocity Distribution in Channel

Velocity distributions were measured at the exit of the channel by the total pressure tube which was inserted as shown in Fig.1. Figure 5 shows the comparison of the velocity distribution between the smooth and the rough wall channel. Symmetrical distributions for the middle section are obtained. The velocity gradient near the

Table 1 Roughness of sand papers

Sand paper	Ra [μm]	Rz [μm]
#40	104.5	419
#80	68.1	279
#180	30.7	126
Smooth	0.35	

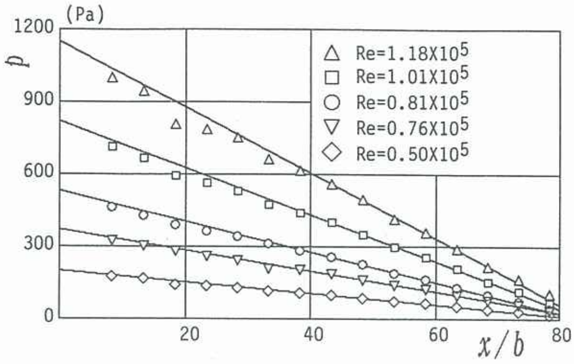

Fig.2 Pressure distribution in channel (b = 30mm, Ra = 104μm)

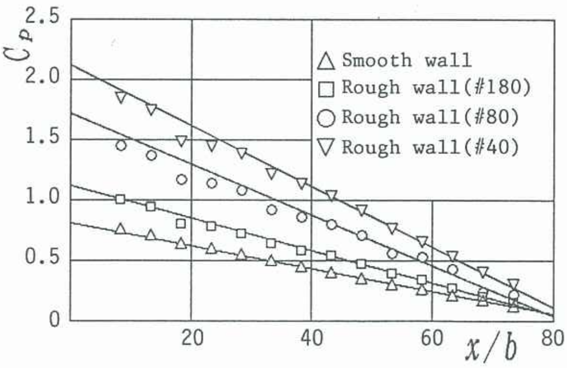

Fig.3 Variation of Cp-distribution with wall roughness (b = 30mm, Re = 1.18 $\times 10^5$)

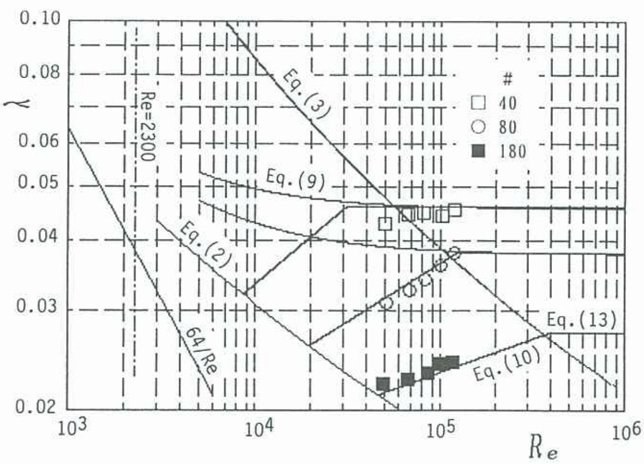

Fig.4 Effect of roughness on friciton loss coefficient (b = 30mm)

rough wall is less steep than that near the smooth one.

Figure 6 shows the logarithmic velocity distribution. For the smooth wall, the well known equation (4) is plotted.

$$u^+ = (1/0.4)\ \ln(y^+) + 5.5 \qquad (4)$$

The distribution for the smooth wall agrees well with Eq.(4). Although the u^+-distribution for the rough wall shows a parallel straight line with respect to Eq.(4), the distribution is less than the distribution of the smooth one and shifts by ΔB. The following experimental equation of Prandtl et al. for ΔB is well known.

$$\Delta B = (1/0.4)\ \ln[1 + 0.3(U\tau \cdot Ks/\nu)] \qquad (5)$$

From this equation, we obtain Ks by substituting ΔB.

On the other hand, the velocity distribution (6) for the rough wall based on Ks is known.

$$u^+ = (1/0.4)\ \ln(y/Ks) + B \qquad (6)$$

For hydraulically smooth regime,

$$B = (1/0.4)\ \ln(U\tau \cdot Ks/\nu) + 5.5 \qquad (7)$$

For completely rough regime,

$$B = 8.5 \qquad (8)$$

Figure 7 shows the distribution of the roughness function B with the roughness Reynolds number($U\tau Ks/\nu$) for all the results for the rough wall. B=8.5 is obtained for the completely rough regime and the distribution of B in the transition regime is not different from the previous results.

Discussion of Loss Coefficient for Rough Wall

When the friction loss for the rough wall pipe is calculated, the loss coefficient is determined from the well known Moody chart and so on by using the equivalent sand roughness Ks. This chart is based on the following Colebrook equation.

$$1/\lambda^{1/2} = -2.0 \log[Ks/3.7 + 2.51/(Re \cdot \lambda^{1/2})] \qquad (9)$$

From this equation, Ks is obtained by substituting the experimental friction coefficient. On the other hand, from the velocity distribution, Ks is obtained from Eq.(5) by using ΔB. The former is called Ks1 and the latter Ks2.

Figure 8 shows the variation of Ks/Ra of both of the values with the Reynolds number. The difference between both of Ks1 and Ks2 is small, but Ks/Ra is dependent on the roughness and the Reynolds number. Therefore, the simple correlation between Ks and Ra is not determined.

By substituting the mean value Ks which is determined for the completely rough regime, the line of Eq.(9) in Fig.4 is obtained. The experimental loss coefficient agrees with Eq.(9) for that regime. Consequently, Eq.(9) seems to be applied for the completely rough regime. However, since Ks/Ra is varied with the roughness and the hydraulic mean depth, this is not practically useful. The empirical equation based on Ra/4M is obtained from this experiment.

$$\lambda = 0.0362\ (Ra \times 10^3/4M)^{0.4} \qquad (10)$$

The following Kárman-Nikuradse equation for the completely rough regime is well known.

$$1/\lambda^{1/2} = 1.14 - 2.0 \log(Ks/4M) \qquad (11)$$

By using our recommended correlation (12)(Akaike et al., 1992), the loss coefficient λ_{KN} can be calculated from Eq.(11).

$$Ks = 8 \cdot Ra \qquad (12)$$

The comparison between λ_{KN} and λ_T which is obtained from Eq.(10) is shown in Fig.9. Figure 9(a) shows both of the values for Ks/4M from 0.0001 to 0.1 and Fig.9(b) the difference between them. The conventional value obtained from Eq.(11) by using Eq.(12) is large compared with this experiment for $Ks/4M \lesssim 0.001$. However, the difference between them for $Ks/4M \gtrsim 0.001$, where λ is large, is small. It is noted that the conversion of Eq.(12) for the friction loss calculation is practically useful for the completely rough regime.

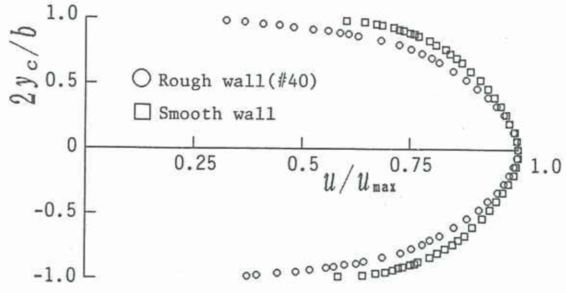

Fig.5 Velocity distribution in channel (b = 30mm, $Re = 1.18 \times 10^5$)

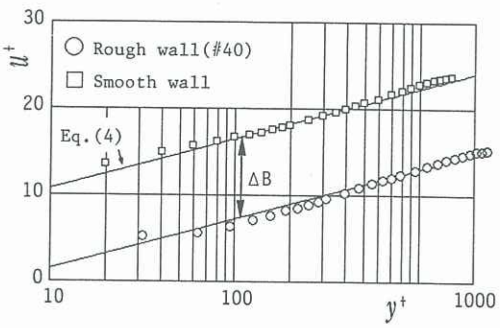

Fig.6 Logarithmic velocity distribution (b = 30mm, $Re = 1.18 \times 10^5$)

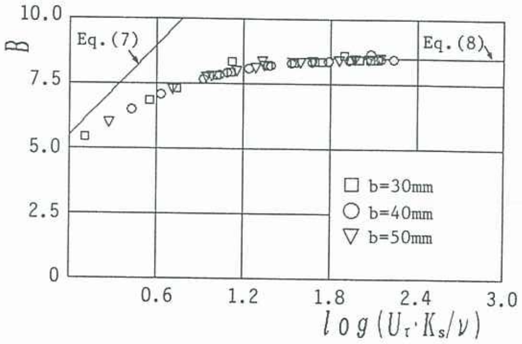

Fig.7 Roughness function B versus roughness Reynolds number

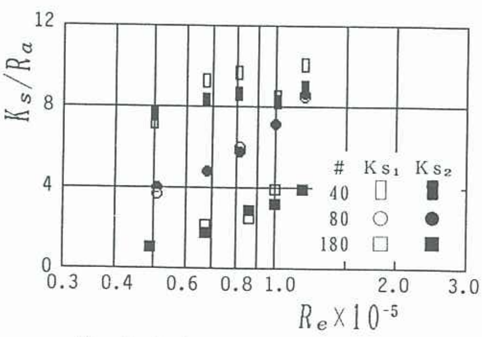

Fig.8 Ks/Ra versus Reynolds number

On the other hand, the friction coefficient for the transition regime does not agree with the Colebrook equation (9) as shown in Fig.4. It is known that the friction characteristics in the transition regime are varied with the types of roughness geometry (Reynolds, 1974). The object of this study is to make clear the friction loss of a surface which is used in such as turbomachinery and is covered closely spaced rough elements. In the case of this experiment, the coefficient in the transition regime is less than that of the completely rough regime. The following empirical equation is obtained for the transition regime.

$$\lambda = 0.00367\,(Ra\times 10^3/4M)^{-0.67}\cdot Re^{A} \qquad (13)$$

Here, $A = 0.19\,(Ra\times 10^3/4M)^{0.66}$.

The friction coefficient depends on Ra/4M and Re. This equation agrees well with the experimental results as shown in Fig.4. It is desirable to obtain more simple equation. We intend to continue further experiments in the wide range of the Reynolds number and revise the equation. The equations (10), (13) have the parameter $Ra\times10^3/4M$. Practically, it is better to use this, because Ra is commonly expressed by unit μm and M by mm and then we can substitute directly Ra[μm]/4M[mm] into Eqs.(10),(13).

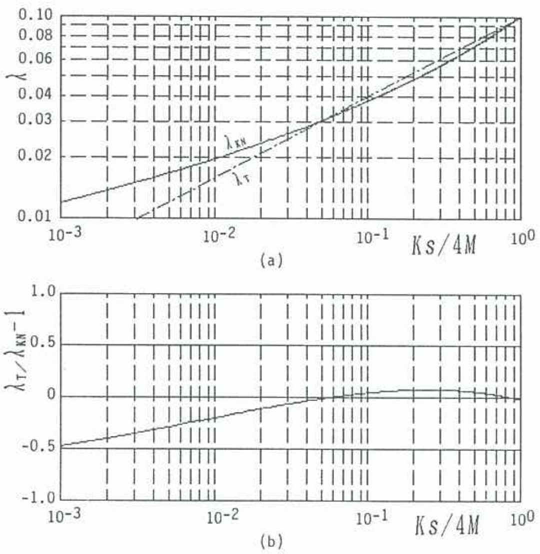

Fig.9 Comparison of friciton coefficient for completely rough regime

Figure 10 shows the friction loss coefficient chart based on Ra/4M to the Reynolds number. In the figure, all the experimental friction coefficients are plotted. This is useful for the practical rough passage under the present conditions. In the range of $Ra/4M < 0.2\times10^{-3}$, there is no transition regime according to the chart. Further studies in the range of the high Reynolds number are needed.

CONCLUSIONS

Experimental study was carried out for the two-dimensional channels which were different from the wall roughness. The pressure and the velocity distributions in the channels are made clear. For the friction loss coefficient, the correlation between Ks and Ra is discussed. The empirical equations for the coefficient based on the relative roughness of Ra/4M are obtained for the transition and the completely rough regimes, respectively.

ACKNOWLEDGMENTS

The authors wish to acknowledge that these experiments have been undertaken with the aid of Mr. N. Ishiwata and Mr. H. Ohta.

REFERENCES

AKAIKE, S(1991) Effects of surface roughness on performance estimation of turbomachinery, Part 1 and Part 2. Turbomachinery 19-12, 776-806(in Japanese).

AKAIKE,S, JINBO,M, NAKANE,I and NEMOTO,M (1992) Inlet flow in two-dimensional channel with rough wall. Proc Inter Conf on Pumps and Systems, Beijing, China, 308-317.

DEAN,R.B.(1978) Reynolds number dependence of skin friction and other bulk flow variables in two-dimensional rectangular duct flow. Trans. ASME, J. Fluids Engineering, 100, 215-223.

REYNOLDS,A.J.(1974) Turbulent flows in engineering. John Wiley & Sons, 206.

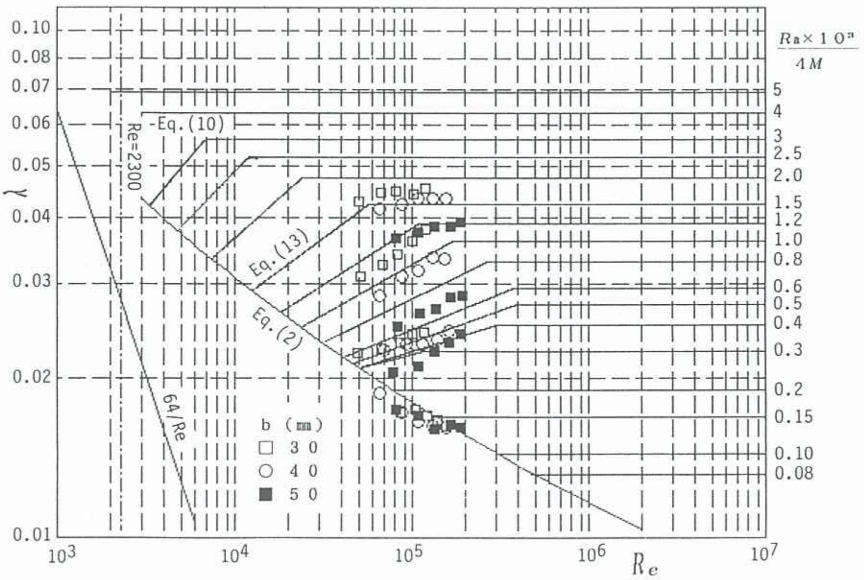

Fig.10 Friction loss corfficient for practical rough wall