Wall roughness characterization in turbulent flow

by Gary Stephen Slanina

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mechanical Engineering
Montana State University

Abstract:
Flow resistance characteristics were obtained for turbulent flow of air in rough pipes. Two rough pipes which were characterized by relative roughnesses (R/k) of 26.4 and 208 were utilized in conjunction with a closed system wind tunnel. A detailed examination of the actual rough surface protrusions indicated that the relative roughness values should be more closely approximated by values of 513 and 38.1. However, friction factors were in close agreement with those of Gow^5 and Powe^6, who utilized the same experimental system. Surface roughness data were also obtained. Several different attempts were made to correlate these data with Hikuradse's equivalent sand diameter. Only the mean height data proved significant. For. the two roughnesses examined, the equivalent sand diameter was seen to be approximately proportional to the mean height of the roughness protrusions. The constant of proportionality obtained was 2.6.

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Signature Gary Stephen Slanina

Date November 21, 1972

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NOMENCLATURE

Symbol	Description
A	Area
c d	Empirical Constant
D	Pipe Diameters
k	Mean Roughness Height
K	Empirical Constant
K_s	Nikuradse's Equivalent Sand Diameter
n	Number of Points
N_R	Reynolds Number $\frac{U_{avg} D}{\nu}$
$\overline{P}$	Mean Static Pressure
R	Pipe Radius
U	Local Velocity
U_{avg}	Bulk Mean Velocity
U_{max}	Centerline Mean Velocity
U^*	Shear Velocity $(T_o/\rho)^{\frac{1}{2}}$
U^+	Dimensionless Mean Velocity (U/U^*)
X	Point Gage Reading
$\overline{X}$	Mean Point Gage Reading
Y	Radial Distance, $Y = o$ is the wall
Y^+	Dimensionless Distance Parameter (YU^*/ν)

Symbol	Description
Z	Axial Coordinate
ν	Kinematic Viscosity
T_o	Wall Shear Stress
λ	Friction Factor
σ	RMS Height
ρ	Fluid Density
μ	Absolute Viscosity

ABSTRACT

Flow resistance characteristics were obtained for turbulent flow of air in rough pipes. Two rough pipes which were characterized by relative roughnesses (R/k) of 26.4 and 208 were utilized in conjunction with a closed system wind tunnel. A detailed examination of the actual rough surface protrusions indicated that the relative roughness values should be more closely approximated by values of 513 and 38.1. However, friction factors were in close agreement with those of Gow[5] and Powe[6], who utilized the same experimental system. Surface roughness data were also obtained. Several different attempts were made to correlate these data with Nikuradse's equivalent sand diameter. Only the mean height data proved significant. For the two roughnesses examined, the equivalent sand diameter was seen to be approximately proportional to the mean height of the roughness protrusions. The constant of proportionality obtained was 2.6.

CHAPTER I

INTRODUCTION

The study of turbulent flow near smooth and rough surfaces has been, and continues to be, a long standing topic of concern in the field of fluid mechanics. Surface roughness has no effect in laminar viscous flows, so long as the roughness protrusions do not appreciably alter the surface contour. However, in turbulent motions the nature of the flow is intimately associated with any existing surface roughness. A better understanding of the flow phenomena linked to surface roughness would enhance the design of aerodynamic and hydrodynamic vehicles. Also, the prediction of flow resistance behavior for existing rough surfaces could be accommodated without the necessity of extensive experimental data taken in connection with actual flow conditions. A recent study by Dipprey[1] has shown the rough surface to be a more effective heat transfer surface when compared with the smooth surface in a restricted range of Prandtl and Reynolds numbers. On the other hand, the problems encountered in rocket engine and nuclear reactor cooling frequently dictate increases in heat transfer at the expense of the required increase in pumping power. This fact coupled with the study of Dipprey indicates that the desirable effect of increased heat transfer may be attained through the proper selection of artificial surface roughness. However, a rational selection or determination of surface roughness remains a major problem.

Empirical correlations and semi-empirical theories are available for predicting both the flow resistance and the heat transfer in rough pipes (see Schlichting[2]), and satisfactory results can be obtained from these methods. The major drawback encountered in using all these correlations and theories is that a knowledge of an equivalent sand diameter for the roughness particles is required. This equivalent sand diameter must be obtained by comparison of flow resistance data from the fully rough regime with data gathered by Nikuradse[3]. However, recent studies[4,5,6] have indicated that the equivalent sand diameter, as obtained from the comparison with Nikuradse's[3] data, is an arbitrary characterization of a pipe roughness. In all these studies the equivalent sand diameter has been found to be larger than the average height of the roughness particles, and the ratio of these two sizes increases as the actual sand size increases. Thus, this method of analysis is satisfactory for existing surfaces where flow resistance can be experimentally measured, but it provides absolutely no means for selecting a roughness size so that a surface may be designed to yield a given flow resistance or desired heat transfer characteristics. It would therefore, be extremely desirable, from a design standpoint, to have available a method for selecting a roughness size to produce desired flow resistance and/or heat transfer characteristics.

The primary purpose of this study will be to perform a statistical analysis of two types of sand grain roughness particles in conjunction with turbulent flow to determine some physically measurable geometric significance for the equivalent sand diameter.

CHAPTER II

LITERATURE REVIEW

Gross flow occurrences in rough pipes are characterized by the friction factor defined as

$$\lambda = \frac{8 \tau_o}{\rho U_{avg}^2} \qquad 2.1$$

Blasius was the first investigator to definitely state that the friction factor should be a function of both the pipe Reynolds number and a roughness parameter. Since his time it has been well established that for a given shape of conduit and kind of roughness,

$$\lambda = f(N_R, k/R) \qquad 2.2$$

where $N_R = U D/\nu$ is the pipe Reynolds, $\nu = \mu/\rho$ is the fluid kinematic viscosity, and k is a linear measure of the wall roughness. The term k/R is commonly referred to as the relative roughness, with R being the pipe radius.

In 1933 Nikuradse[3] published the results of a study of a series of sand roughened pipe tests using water as the test fluid. Nikuradse[3] obtained sand grains which were to be used as roughness elements by sifting between standard screen sizes. The roughness elements thus obtained were of a rather uniform height and yielded a somewhat random shape distribution. Although the use of sand grains as roughness elements is somewhat artificial, it is generally found that all other roughness types behave in much the same manner in fully rough flow (i.e. that flow regime where the viscous sublayer becomes thick enough such that the roughness elements are supposed to extend completely into the turbulent core of flow). It is this region, the region of interest in this study, for which Nikuradse determined the following friction factor relationship

$$\lambda = \frac{1}{(1.74 + 2\ \mathrm{LOG}(R/k))^2} \qquad 2.3$$

where, following Nikuradse, k is the average depth of roughness. Equation 2.3 indicates that the friction factor is independent of the Reynolds number and a function only of the relative roughness R/k.

Since Nikuradse's work it has become common practice to express the roughness of a pipe of unknown roughness in terms of an equivalent sand diameter. In actual practice this is done by measuring the friction factor, as defined in equation 2.1, in the fully rough flow regime and then, using equation 2.3, calculating the equivalent sand roughness K_s which would yield this same friction factor.

Recent investigators[4,5,6] however, have indicated that, for large roughnesses, a sand diameter as obtained from the average screen sizes is significantly smaller than the equivalent sand diameter as obtained from equation 2.3. Robertson[4] et al. found the ratio of the equivalent to the average roughness height to vary from 1.03 to 1.35 while considering the flow of air in a 3 inch diameter pipe, while

Gow[5] and Powe[6] obtained values of 1.0 to 2.3 using air in a 12 inch diameter pipe. Thus, there is a strong indication that the equivalent sand diameter is an arbitrary characterization of a surface roughness.

More recently, Brown and Chu[7] have conducted experiments to determine whether a root-mean-square value of rough surface protrusions is related to the Nikuradse equivalent sand diameter for open channel flow. Although their conclusions seem to contradict their results, the rms concept does merit deeper investigations.

DeVor and Wu[8] introduce the use of parametric stochastic models of the autoregressive-moving average (ARMA) class for surface profile description. The authors consider three basic structural components in a typical surface profile.

1. Waviness or secondary texture
2. Roughness or primary texture
3. Surface lay or errors of form

The three structural components of the profile are classified mathematically as arising from two basic elements of the total profile variation: (a) a deterministic element and (b) a stochastic element. The deterministic element comprises the waviness or periodic trend in the profile. The stochastic element encompasses both roughness and error of form.

The authors point out that their autocorrelation theory and spectrum analysis used in the stochastic modeling within the framework of ARMA modeling should be used only as tools for model identification and are not put forth as models for surface profiles. Furthermore, the ARMA modeling technique seems primarily suited for surfaces produced by the more sophisticated machining techniques such as milling and boring.

It is clearly evident that much work needs to be done in the area of surface roughness characterization before the designer can make a rational selection of a surface roughness for optimization of flow resistance and heat transfer characteristics.

CHAPTER III

EXPERIMENTAL SYSTEM

The experimental system illustrated schematically on Figure 1 was employed throughout the investigation. It is essentially the same system as that employed by Powe[6] and Gow[5]. Because the system had been down for a period of one year for relocation purposes it was necessary to repeat the flow resistance recording as Robertson[4] et al. noticed a pronounced effect on pipe roughness when their system had been left idle for longer than a year. The experimental system consists of a closed circuit wind tunnel comprised of one foot diameter aluminum irrigation pipe. Constant temperature hot wire anemometry apparatus is included with the system.

Air is discharged from a centrifugal fan into an approximately two foot diameter flexible duct. Flow rates are controlled with a manual damper on the inlet side of the fan. The entrance section (see Figure 2) contains a baffle plate and a series of screens to filter the air and dampen turbulence from the fan and return line. The cross section of the entrance is reduced to slightly above one foot square through a transition section in the form of a quarter sine wave. Transition from the square cross section to the one foot diameter circular cross section is obtained through a short tapered sheet metal duct. Sixty-five feet of aluminum pipe are used to ensure

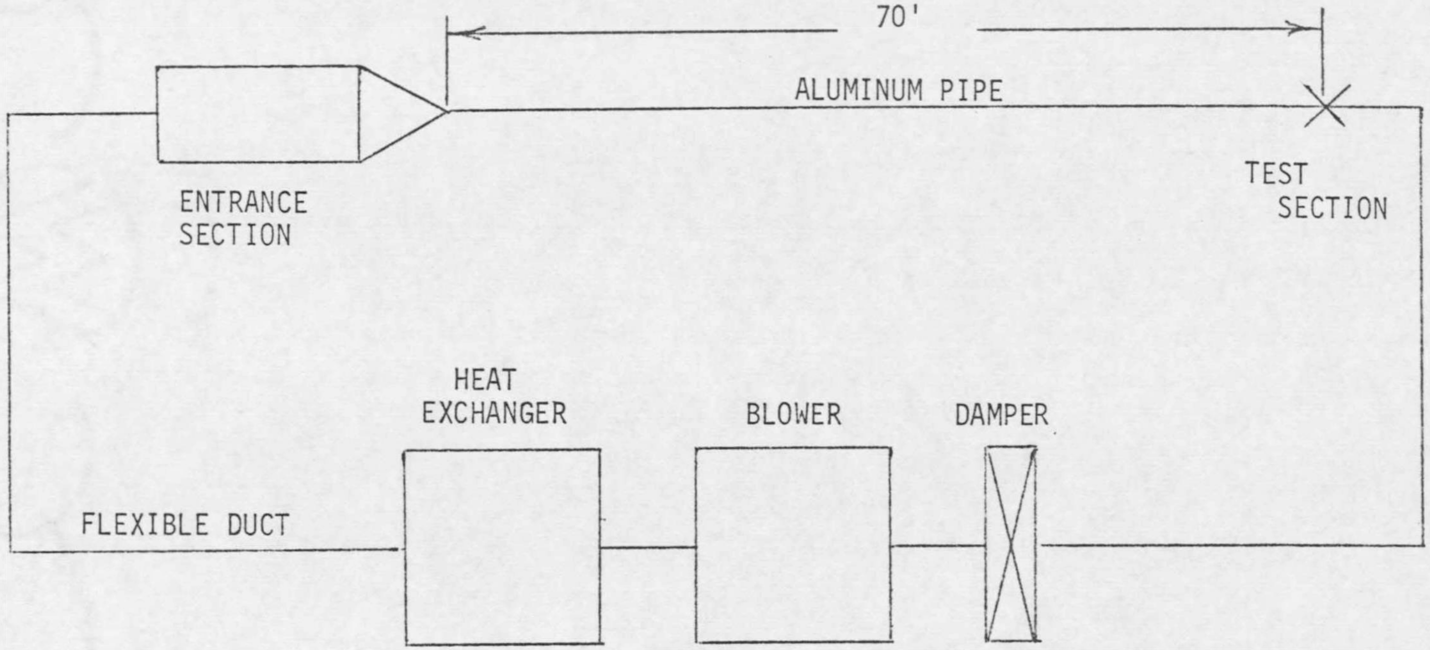

FIGURE 1. SCHEMATIC REPRESENTATION OF THE WIND TUNNEL