Measurements in a Wall Jet with and without a Trip Wire

By Hideo OSAKA* and Hidemi YAMADA*

(Received July 15, 1978)

Abstract

The effect of a trip wire on the development of a two-dimensional turbulent wall jet was investigated by comparison of the flow field between with and without a trip wire near the slit nozzle. Present study is mainly examined from the viewpoints of mean velocity. The available velocity and length scales for the wall jet were proposed, and discussed with respect to the self-preserving. The cross-stream static pressure was measured in detail, we thus obtained $dp/dy \fallingdotseq 0$.

1. Introduction

It is now well known that the wall jet has the character of both free jet and boundary layer. Consequently, its flow fields are so complicated that most of analysis cannot but rely on the experimental investigations. Up to date, the various types of turbulent wall jet have been investigated by many authors1)~6). Turbulent structure, however, still has not been confirmed, even if the problems were confined to the plane wall jet. It may be one reason why prevents the understanding of the wall jet flow that the previous experiments are different slightly one another. There may be the cases that these results include even the essential difference with respect to turbulent structure in some sense. So, the characteristic quantities of wall jet should be compared only under the same basic conditions, for example, the dimension of the boundary layer at the slit nozzle, the existence of free-stream outside the wall jet flow and the presence of a trip wire on the flat plate near the slit nozzle, etc.. Thus, it may be dangerous to mislead that the various data are identified without a comparison of each flow condition.

In the present experiment, therefore, the effects of a trip wire on the wall near the slit on the flow structure were examined for the wall jet having no free-stream outside, which was the most basic flow. For the purpose of comparing the developments of the flow, it will be found that the reference transverse scale is better than the longitudinal distance from the virtual origin. The similarity of the flow field will be discussed as compared the reference length and velocity scales based on the measurements with those obtained from the self-preserving condition.

Nomenclature

P = mean static pressure
Pa = atmospheric pressure

---

* Mechanical Engineering

S = slit height (= 10 mm)
U, V = mean velocities in x and y directions
U_m = maximum velocity at a fixed x
U_0 = mean velocity at the center line of slit
u', v' = turbulent velocities in x and y directions
x = distance measured along wall surface in main stream direction from the slit
y = distance normal to surface
δ_m = position of U_m above surface
δ_2 = position above surface where $U = U_m/2$
θ^* = momentum thickness in the inner layer
δ^* = displacement thickness in the inner layer
τ_0 = wall shear stress
C_f = local skin friction coefficient, $\tau_0/(1/2)\rho U_0^2$
C_p = non-dimensional static pressure coefficient, $\left\{(P-Pa)\Big/\left(\frac{1}{2}\right)\rho U_i^2\right\}\times 100$
x_w = distance from the slit to a trip wire

2. Experimental Apparatus and Techniques

The apparatus used in this expreiment is shown schematically in Fig. 1. The wall jet develops on a measuring flat plate with 300 mm wide, 1280 mm long. A variable speed Ringcone motor drives the centrifugal blower. In the settling chamber are set four screens; two screens having an open area ratio β of 0.6 (wire dia. of 0.45 mm) and another two of 0.64 (wire dia. of 0.35 mm) respectively. The flow is contracted, at first, from 300 × 300 mm to 300 × 30 mm, and next is led to the nozzle slit of 10 mm height. The maximum velocity at the nozzle exit is about 40 m/s. Measurements were made at a single value of Reynolds number; 2×10^4.

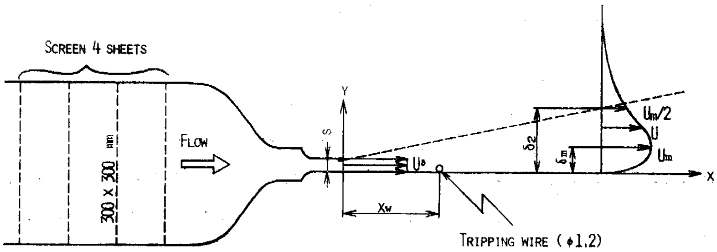

Fig. 1 Flow system.

Mean velocity and turbulent intensity distributions were measured by means of a total-pressure probe with square-ended flattened section (0.3 mm height) and I-shaped sensor probe (5 μm wire dia.) with a constant temperature anemometer system respectively. Static pressure was measured by means of the L-shaped static pressure tube[7] with 1.5 mm diameter which had the sufficient "nose to stem" distance. As occasion demands, a trip wire was set at the position of 20 mm downstream from the nozzle exit on the wall.

3. Results and Discussion

3-1. Basic flow fields

Fig. 2 shows the velocity and static pressure profiles at the nozzle exit. Though the boundary layer was produced almost in symmetry at both sides of the nozzle exit, the velocity profile was kept in uniformity over the range of 80% of nozzle height. Static pressure profile tends to be higher in the measuring plate side than in free boundary side, where approximate atmospheric pressure. Turbulent intensity was also about 0.55% at the nozzle exit.

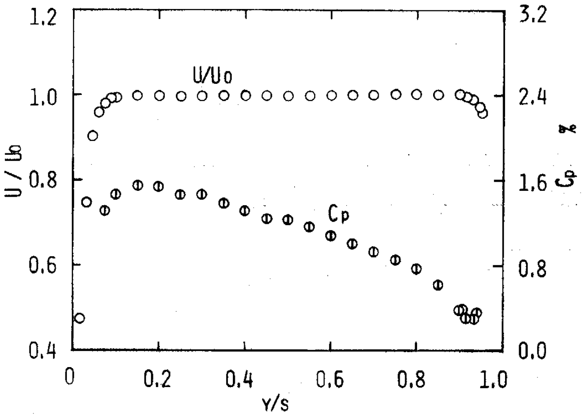

Fig. 2 Mean velocity and static pressure distributions at nozzle slit.

Fig. 3 shows the wall static pressure profile in the cases with and without a trip wire on the measuring wall. The wall pressure with trip wire is higher than that without a trip wire at the position of $x/s=5$ because of the direct effect of a trip wire, but in the downstream region more than $x/s=10$ both tendency agree well in spite of the difference of those magnitude. If the pressure measured on the wall shows the over all pressure in the constant section of x, the pressure gradient for wall jet flow is very small, and may be taken to be zero in the downstream region further than $x/s=40$.

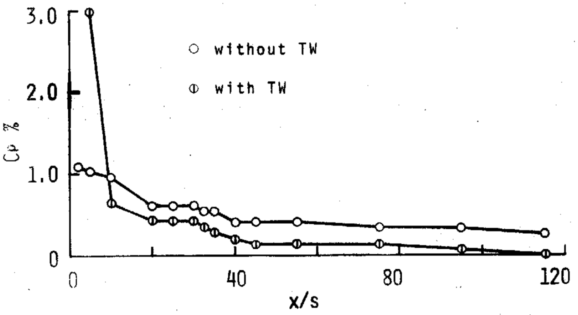

Fig. 3 Variation of wall static pressure distribution.

3–2. Similarity consideration

If a cross-stream scale l as the distance from the wall and a length scale L and a velocity scale Us in the streamwise direction are defined for the wall jet, we may write the followings according to the way of Lumley[8]

$$\partial U/\partial y = O(Us/l), \quad \partial U/\partial x = O(Us/L). \tag{1}$$

In addition to the velocity and length scales just defined, we need a velocity scale for the turbulence. Let us use the symbol u, so that

$$-\overline{u'v'} = O(u^2), \quad \overline{u'^2} = O(u^2), \quad \overline{v'^2} = O(u^2). \tag{2}$$

A scale for the cross-stream component V of the mean velocity can be determined from the mean equation of continuity;

$$V = O(Us \cdot l/L). \tag{3}$$

Here, the equation of motion should be examined in the limit as $l/L \to 0$. The equation for the downstream component U is

$$\begin{aligned} &U \cdot \partial U/\partial x + V \cdot \partial U/\partial y + \partial(\overline{u'^2})/\partial x + \partial(\overline{u'v'})/\partial y \\ &= -(1/\rho) dP/dx + \nu(\partial^2 U/\partial x^2 + \partial^2 U/\partial y^2). \end{aligned} \tag{4}$$

Each term of (4) can be estimated by using the scales introduced earlier. If the Reynolds number is large enough, the viscous terms become very small. Further, we expect that for the wall jet

$$Us \sim u. \tag{5}$$

In the limit as $l/L \to 0$. Under these conditions, other terms of order near $\partial(\overline{u'v'})/\partial y$ are needed to balance the equations, that is

$$U \cdot \partial U/\partial x + V \cdot \partial U/\partial y + \partial(\overline{u'^2})/\partial x + \partial(\overline{u'v'})/\partial y = -(1/\rho) \cdot dP/dx. \tag{6}$$

From the imposed condition of flow fields, (6) may be approximated by

$$U \cdot \partial U/\partial x + V \cdot \partial U/\partial y + \partial(\overline{u'^2})/\partial x + \partial(\overline{u'v'})/\partial y = 0. \tag{7}$$

In the followings, if the concept of self-preservation will be led for wall jet, we may describe the non-dimensional quantities as follows;

$$\left.\begin{aligned} &U = Us \cdot f(\xi), \quad -\overline{u'v'} = Us^2 \cdot g(\xi), \quad \overline{u'^2} = Us^2 \cdot h(\xi) \\ &\xi = y/l, \qquad l = l(x), \qquad Us = Us(x). \end{aligned}\right\} \tag{8}$$

Substituting (8) into (7), we obtain

$$\frac{l}{Us} \cdot \frac{\partial Us}{\partial x} \cdot f^2 - \xi f' f - \frac{l}{Us} \frac{dUs}{dx} f' \int f \cdot d\xi + \frac{dl}{dx} \xi f'^2 + 2 \frac{l}{Us} \frac{\partial Us}{\partial x} h - \xi h' = g'. \tag{9}$$

The existence of the self-preservation requires that each term of (9) must be independent of x, so that we need

$$\frac{l}{Us}\cdot\frac{dUs}{dx}=\text{const.},\quad \frac{dl}{dx}=\text{const.}. \tag{10}$$

Then we obtain

$$l\sim x,\quad Us\sim x^n. \tag{11,12}$$

A half-width δ_2 and a maximum velocity U_m are often taken conveniently for l and Us respectively in wall jets and free jets.

Here, for wall jets consider the over all scales of velocity and length defined by

$$U_i=\int_0^\infty U^2\cdot dy\Big/\int_0^\infty U\cdot dy,\quad l_i=\left(\int_0^\infty U\cdot dy\right)^2\Big/\int_0^\infty U^2\cdot dy.$$

These may be considered as corresponding to Us and l. Since two velocity scales U_m, U_i vary as $x^{-1/2}$ as shown in Fig. 4, the value of n in (12) can be experimentally taken as $-1/2$. Also, we found that mean velocity in the case with a trip wire decayed, with keeping the same power of x, faster than that in the case without a trip wire. Fig. 5 shows the change of length scales δ_2 and l_i in the x direction. Both δ_2 and l_i can be expressed in the same form, which tend to be slightly different from (11), that is, approximately

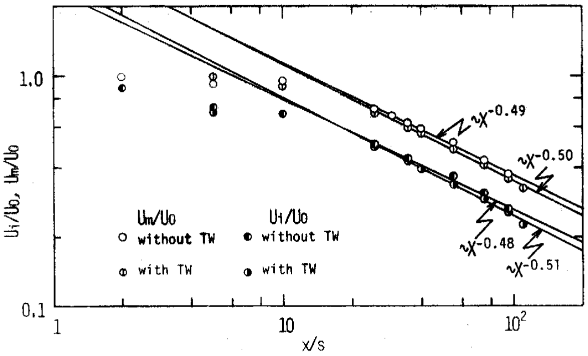

Fig. 4 Variation of velocity scales.

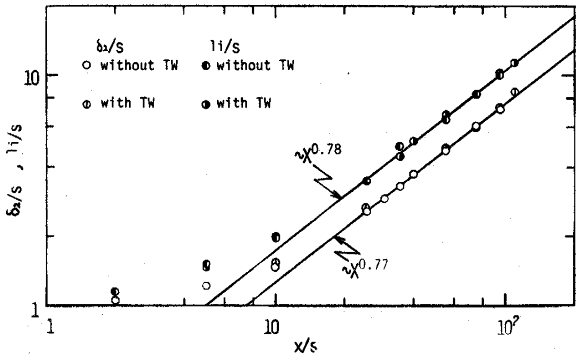

Fig. 5 Variation of length scales.

$$\delta_2,\ l_i \sim x^{4/5}.$$

It is found from Fig. 5 that length scales almost never alter, although velocity scales alter by the existence of a trip wire. Therefore, the use of transverse scales δ_2, l_i may be more suitable than the streamwise distance x when compared with each experiment having the different conditions of flow field. In this experiment, the flow seems to be similar in the region where the data of reference scales are plotted on the full line shown in Fig. 4 and Fig. 5, that is, in the downstream region further than about $l_i/s=3$ or $x/s=20$.

A problem is still remained with respect to (7). It is that, as shown in Fig. 6, although the cross-stream variation in the non-dimensional pressure is large more and more to the downstream direction, the contribution due to the cross-stream momentum is neglected in (7) and dp/dx is assumed to zero.

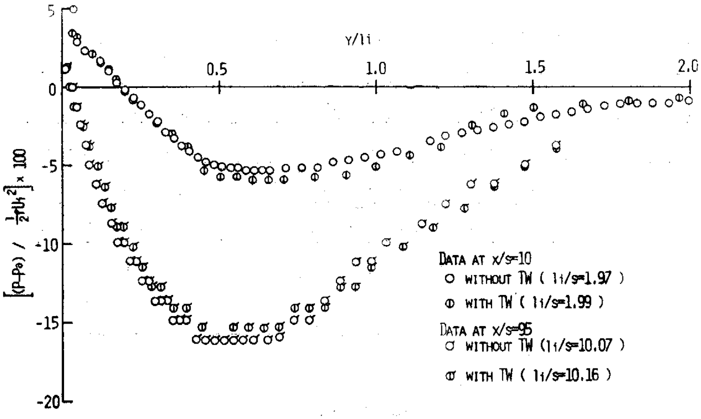

Fig. 6 Static pressure distributions.

3–3. Mean velocity and turbulence intensity profiles

Fig. 7 shows mean velocity profiles at the position corresponding to the value of $l_i/s=6.5$ and 10, that is $x/s=55$ and 95 respectively. Mean velocity profiles expressed by using l_i and U_i are almost similar, even though in the case that the development of U_i is influenced by the existence of a trip wire. This tendency is found in the downstream region which have the same value as l_i/s larger than about three times of it. Consequently, a systematical distinction in the profiles of mean velocity due to the existence of a trip wire is not appear with respect to development in the x direction.

The distribution of the turbulent intensities is shown using the local scales l_i and U_i in Fig. 8. The turbulent intensity profile is still developing in the region where mean velocity profile has a similar shape. The magnitude of the turbulent intensity in the wall jet is much higher than that in the flat plate boundary layer, and has the same value as that in the free-shear flow like jet and mixing layer. This result will be thought to depend on the difference of entrainment between wall jets and boundary layers. It is found that the presence of a trip wire influences the turbulent intensity distribution explicitly while it doesn't affect the mean velocity directly.

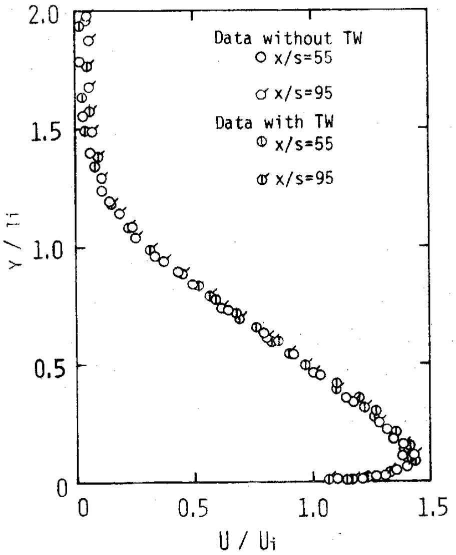

Fig. 7 Similarity of velocity distribution.

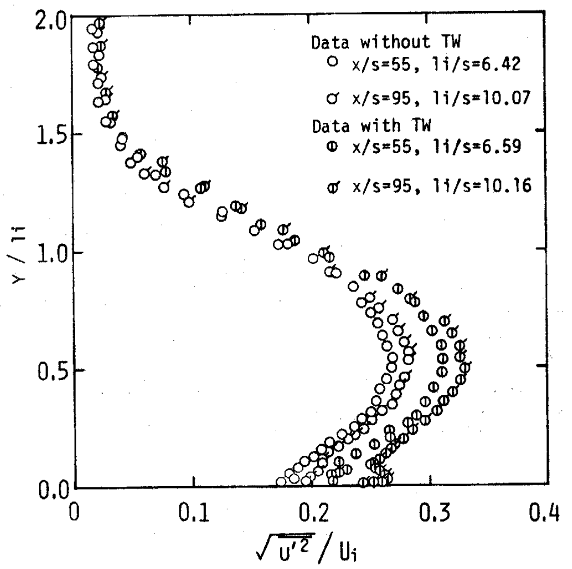

Fig. 8 Similarity of turbulent intensity distribution.

3-4. Developments of flow field

The development of flow field can be predicted by using the reference scales, that is, U_i and l_i mentioned previous in some degree. So, we need to examine how the development of these scales coincides with other characteristic quantities of wall jets such as the skin friction, the shape factor, etc.. None may still offers a method that determines the skin friction of wall jets correctly and easily.

In this investigation, estimates of the skin friction were attempted by two methods, this is, Preston tube method using the calibration constants of Patel and Clauser chart method using the constants (4.15, 8) of Tailland. Fig. 9 shows the results obtained by these two ways, which include the case with and without a trip wire. The skin friction coefficient for the case without a trip wire agrees well with the result of Myers et al.[2]. On the other hand, the skin friction coefficient for the case with a trip wire

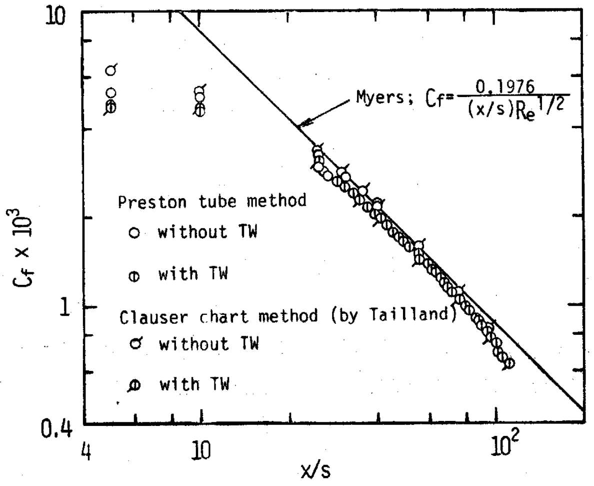

Fig. 9 Local skin friction coefficient.

is slightly small, but keeps the relation of $C_f \sim x^{-1}$ as well as in the case of no trip wire. This result indicates that effect of a trip wire seems to contribute to the consumption of mean velocity momentum.

Fig. 10 shows the change of shape factor δ^*/θ^* for the inner layer in wall jets, which is often used in order to express shapes of the velocity profile for boundary layers. It is of great interest that the value of δ^*/θ^{*}[4] is kept in the constant value of 1.4 which coincide with that of turbulent boundary layer. The shape of velocity profile is, however, different from the 1/7-th power law to say, or rather is well expressed by the 1/14-th power law[1] for values of y larger than 0.3 of y/δ_m as shown in Fig. 11. The present profiles well coincide with the result of Schwarz-Cosart[1] but are different from the result of Kruka-Eskinazi[3] with a moving stream outside a wall jet.

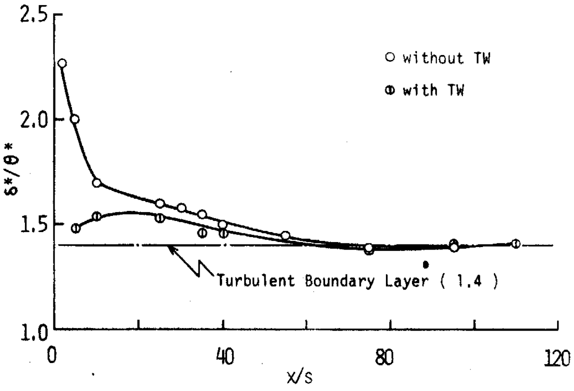

Fig. 10 Variation of shape factor for the inner layer.

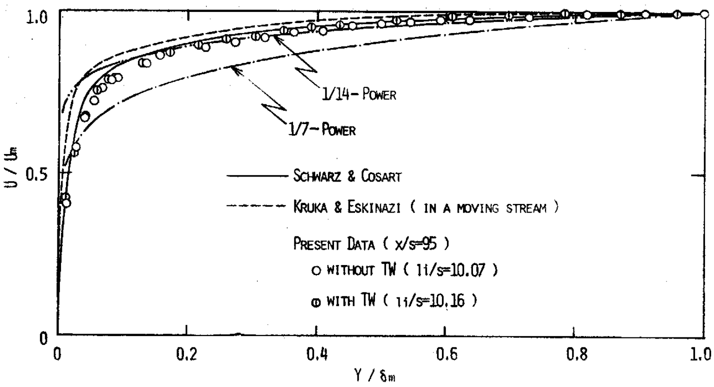

Fig. 11 Comparison of inner layer velocity distributions.

The wall jet may be thought to have approximately two kinds of turbulent flows on the structure. However, the properties in the inner region and outer region of the wall jet, because both region are closely concerned, are entirely different from that of boundary layer and free jet respectively. The existence of this interference can be inferred from the fact that mean velocity profile of the outer layer is not similar based on the difference of entrainment mechanism to that of the plane free jet as shown in Fig. 12. The profiles in the region of $(y-\delta_m)/(\delta_2-\delta_m)<1$ show somewhat smaller values of U/U_m than those predicted, and the profile of the outer layer is likely to be straight on the whole.

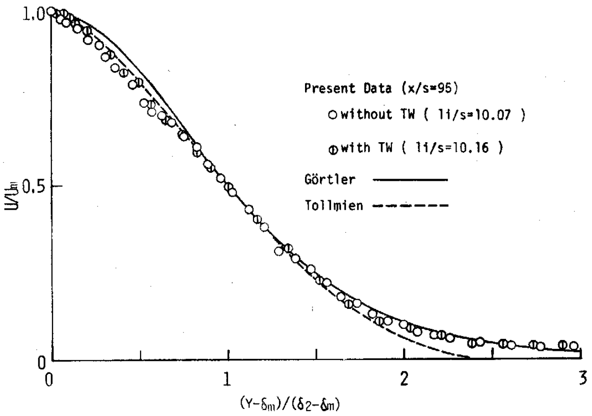

Fig. 12 Comparison of outer layer velocity distributions.

4. Conclusions

Measurements were made for wall jet in full detail in the cases with and without a trip wire. The following have been revealed.

1) In the case when describing by using the local scales U_i and l_i defined, the similarity of mean velocity is satisfied fairly upstream, but turbulent intensity and static pressure are developing gradually in x direction and $dp/dy \fallingdotseq 0$ in the cases with and without a trip wire.

2) Such the length scale as the defined scale l_i and the half width δ_2 are expressed well in $x^{4/5}$ rather than x.

3) Present results are different clearly from results with the free-stream outside with respect to the structure of the inner layer.

4) The structure of the wall jet may not be changed essentially by the existence of a trip wire. Effects of turbulent promoter due to a trip wire seem to be smaller than expected, further exactly, it needs to be examined from the viewpoints of such turbulence properties as the turbulent intensity profile.

Acknowledgement

The author wish to thank S. Yahata and H. Yamasaki for their help.

References

1) Schwarz, W. H. and Cosart, W. P. "The two-dimensional turbulent wall-jet", J. Fluid Mech., **10**, 481–554 (1961)

2) Myers, G. E., Schauer, J. J. and Eustis, R. H. "Plane Turbulent Wall jet Flow Development and Friction Factor," J. Basic Eng., trans. ASME, **85**, 47–54 (1963)

3) Kruka, V. and Eskinazi, S. "The wall-jet in a moving stream," J. Fluid Mech., **20**, 555–579 (1964)

4) Kacker, S. C. and Whitelaw, J. H. "Some Properties of the Two-Dimensional, Turbulent Wall Jet in a Moving Stream," J. Appl. Mech., trans. ASME, **35**, 641–651 (1968)

5) Irwin, H. P. A. H. "Measurements in a self-preserving plane wall jet in a positive pressure gradient," J. Fluid Mech., **61**, 33–63 (1973)

6) Wilson, D. J. and Goldstein, R. J. "Turbulent Wall Jets With Cylindrical Streamwise Surface Curvature," J. Fluids. Eng., trans. ASME, **98**, 550–557 (1976)

7) Vagt, J. D. and Fernholz, H. H. "Wall Interference Effects of Static Pressure Probes in an Incompressible Turbulent Boundary Layer," Aeron. Quarterly, **28**, 176–184 (1977)

8) Tennekes, H. and Lumley, J. L. "A first course in turbulence" (The MIT press) p. 104 (1974)