Laminar and Turbulent Boundary Layer Measurement

12012127　邹佳驹

I. Objective and requirements

Measure the depth of the boundary layer on smooth and rough flat plates.

Master the method of boundary layer measurement.

Understand the structure of the boundary layer.

II. Principles

Boundary Layer Plates

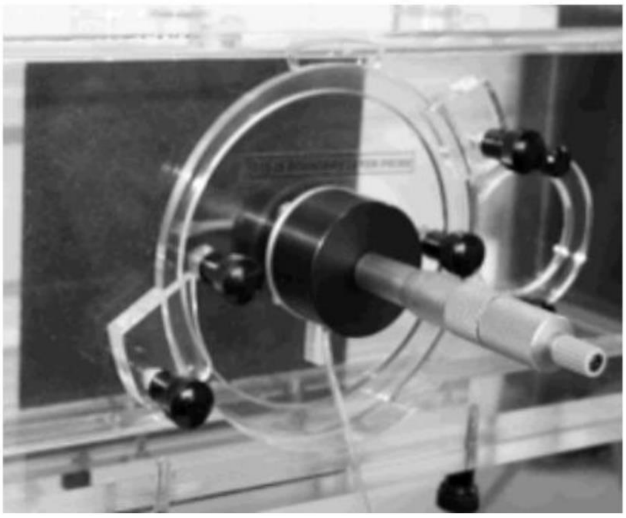
Flat plates including smooth and rough surfaces are mounted vertically in the working section by means of a removable base plate with horizontal slots in order to measure the velocity at any distance from the leading edge.

In this experiment, these distances are 1cm and 2cm.

Flattened Pitot tube

A special flattened Pitot tube (total head tube) is mounted on a traversing micrometer (one scale is 0.01mm) to measure the air velocity at different distances from the surface of the plate. There is a solid rod downstream of the Pitot tip to make the operator notice when the tip is touching the plate and avoid damage to the tip due to excessive movement.

It is worth noting that the air velocity measured using a flat total head tube will not be as accurate as an elliptical Pitot static tube, but it is sufficient to demonstrate the existence of a boundary layer and the variation of the velocity in this experiment.



The flat plate along with the flattened Pitot tube

Boundary Layer

When the uniform airflow (velocity u_0) flows to a flat plate, the velocity immediately adjacent to the surface of the plate is zero due to the viscous effect. As the distance to the surface increases, the velocity gradually increases, and finally returns to the equivalent of the velocity of the non-viscous potential flow. This thin layer section of airflow is called the boundary layer of airflow, the role of viscosity outside the thin layer is almost negligible.

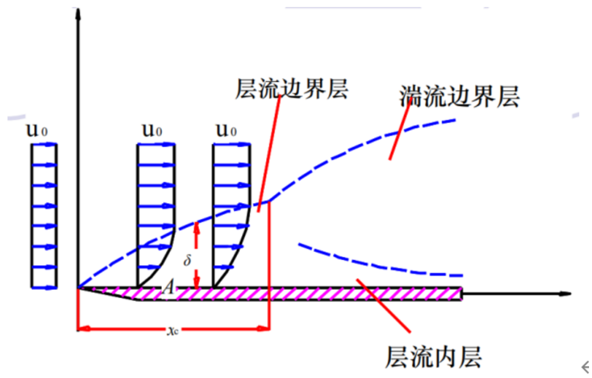
Laminar Boundary Layer

The flow in a laminar boundary layer is smooth, and it’s a series of layers sliding over one another. Skin friction tends to be low and the thickness of the boundary layer tends to be small.

Turbulent Boundary Layer

The fluid moves in small eddies of varying size and strength in a turbulent boundary layer. Skin friction is higher than in a laminar boundary layer, and the boundary layer tends to be thicker.

A change from one type to the other is a boundary layer transition and a rough plate surface tends to encourage the early development of a turbulent boundary layer.



Boundary layer development for plate

Velocity Profiles

The velocity profile obtained by using a Pitot tube varies depending on whether the flow is laminar or turbulent. For turbulent flows, the velocity gradient at the surface is higher.

Boundary layer thickness

For the sake of uniformity, the thickness of the region extending from the solid boundary to the point where the velocity is 99% u_0 is generally referred to as the boundary layer thickness.

Define a characteristic Reynolds number Re_x with the distance x from the leading edge of the plate as the characteristic length scale:

$$Re_x = \frac{\rho x u_0}{\mu}$$

For laminar boundary:

$$\mathrm{u(y)} \sim u_0 \frac{y}{\delta}$$

$$\delta = \frac{5.0x}{\sqrt{Re_x}}$$

For turbulent boundary:

$$\mathrm{u(y)} = u_0 (\frac{y}{\delta})^{\frac{1}{7}}$$

$$\delta = \frac{0.37x}{\sqrt[5]{Re_x}}$$

III. Data processing and results

1.For the four sets of data, determine the main stream speed u_0, and the theory value of boundary layer thickness.

Ambient temperature: 19.8℃

Air density: $\rho_{air} = \rho_0 \frac{273}{273+t} = \frac{1.293*273}{273+19.8} = 1.206\ kg/m^3$

Air viscosity:

according to Sutland's formula

$\mu = \mu_0 * \left(\frac{T}{288.15}\right)^{1.5} * \frac{288.15+B}{T+B} = 1.7894 * 10^{-5} * (\frac{19.8+273.15}{288.15})^{1.5} * \frac{288.15+110.4}{273.15+19.8+110.4} = 1.8125 * 10^{-5} Pa * s$

Main stream speed:

Since the fan speed is set to 60%, the main stream speed can be obtained by averaging the record data, and we get the main stream speed $u_0 = 17.0m/s$

Characteristic Reynolds number:

$$Re_{1cm} = \frac{\rho x u_0}{\mu} = \frac{1.206*0.01*17.0}{1.8125*10^{-5}} = 11311$$

$$Re_{2cm} = \frac{\rho x u_0}{\mu} = \frac{1.206*0.02*17.0}{1.8125*10^{-5}} = 22622$$

1cm from LE

laminar boundary layer

$$\delta_{1l} = \frac{5.0x}{\sqrt{Re_{1cm}}} = \frac{5*10}{\sqrt{11311}} = 0.4701mm$$

turbulent boundary

$$\delta_{1t} = \frac{0.37x}{\sqrt[5]{\mathrm{Re}_{1cm}}} = \frac{0.37*10}{\sqrt[5]{11311}} = 0.5721mm$$

2cm from LE:

laminar boundary layer

$$\delta_{2l} = \frac{5.0x}{\sqrt{Re_{2cm}}} = \frac{5*20}{\sqrt{22622}} = 0.6649mm$$

turbulent boundary

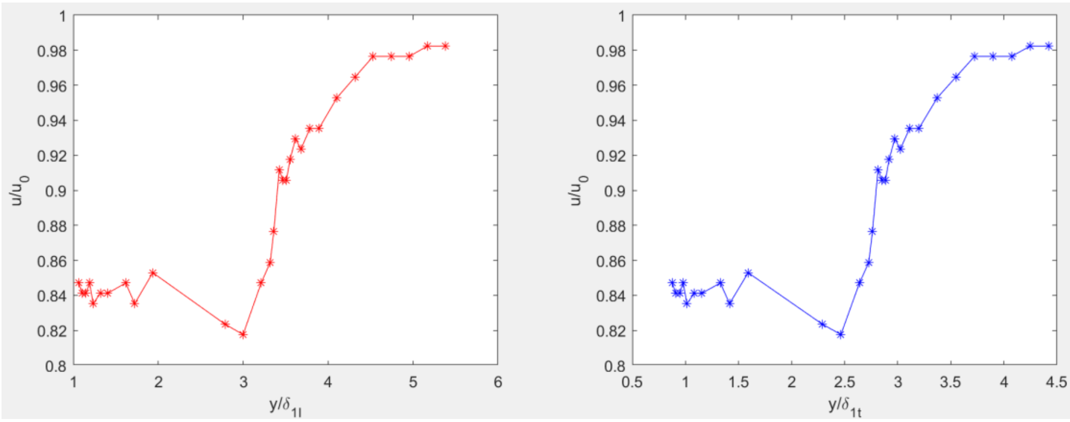
$$\delta_{2t} = \frac{0.37x}{\sqrt[5]{\mathrm{Re}_{2cm}}} = \frac{0.37*20}{\sqrt[5]{22622}} = 0.9962mm$$

2.Plot the scaled Pitot speed (u/u_0) vs the scaled distance from the plate (y/δ).

For smooth plate

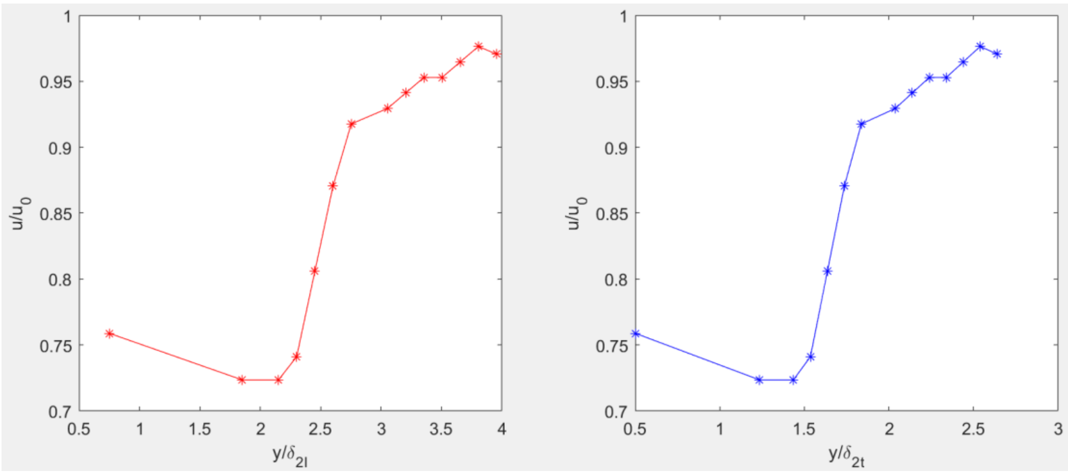
1) 1cm from LE

$$\frac{u}{u_0}\ vs\ \frac{y}{\delta_{1l}}\quad and\quad \frac{u}{u_0}\ vs\ \frac{y}{\delta_{1t}}$$



2) 2cm from LE

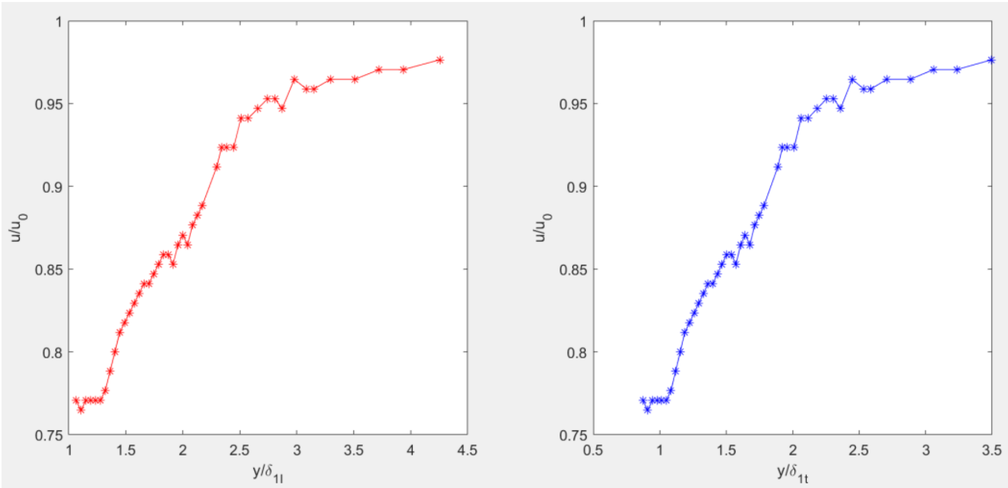
$$\frac{u}{u_0}\ vs\ \frac{y}{\delta_{2l}}\ and\ \frac{u}{u_0}\ vs\ \frac{y}{\delta_{2t}}$$



For rough plate

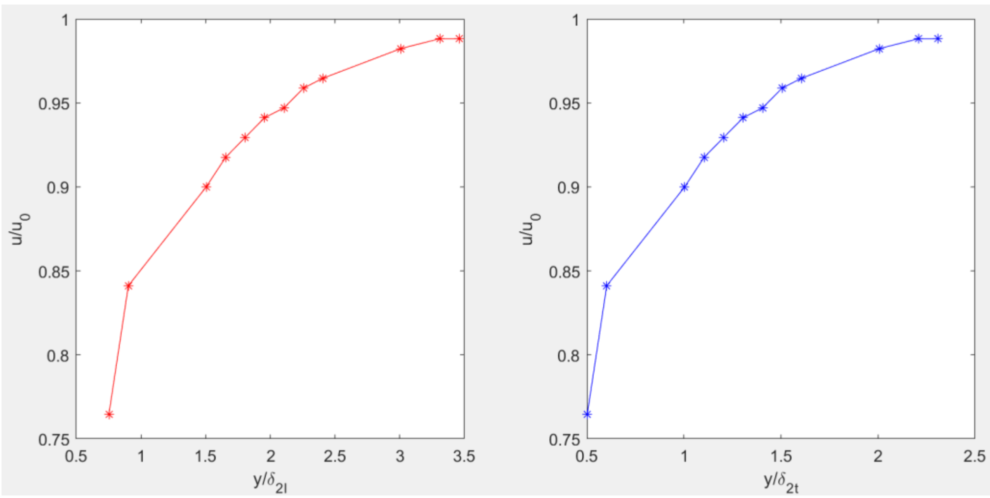
1) 1cm from LE

$$\frac{u}{u_0}\ vs\ \frac{y}{\delta_{1l}}\quad and\quad \frac{u}{u_0}\ vs\ \frac{y}{\delta_{1t}}$$



2) 2cm from LE

$$\frac{u}{u_0}\ vs\ \frac{y}{\delta_{2l}}\ and\ \frac{u}{u_0}\ vs\ \frac{y}{\delta_{2t}}$$



3.Analyze the boundary type and whether the measured value is consistent with the theoretical value.

Analyzing the above figures and experimental data,
the boundary layer thicknesses obtained by the experiment are:
Smooth plate
1cm position from leading edge: 2.43mm
2cm position from leading edge: 2.53mm
Rough plate
1cm position from leading edge: 2.00mm
2cm position from leading edge: 2.30mm

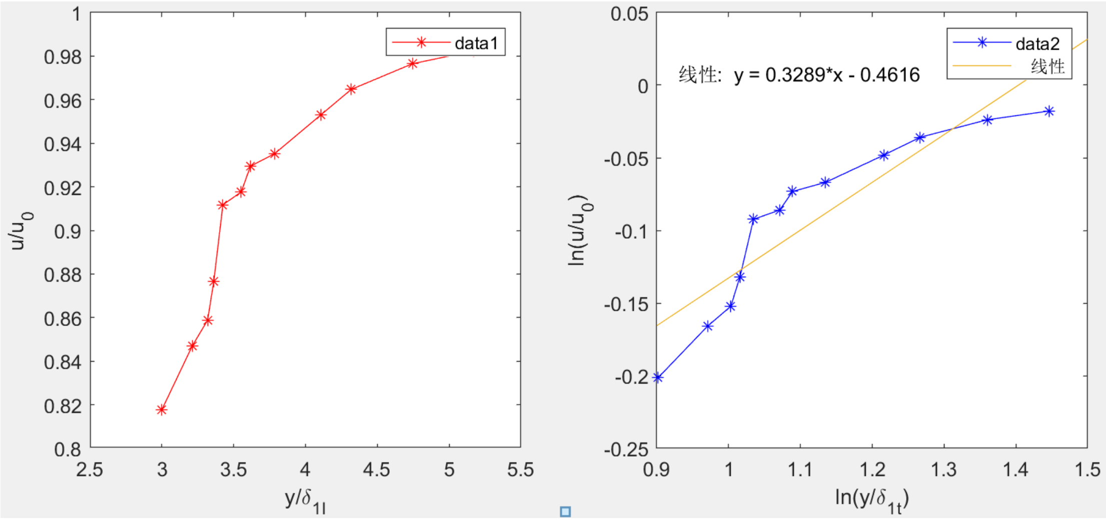
Obviously, the experimental measurements are greater than the theoretical values.
Sources of error could be:
1) The air velocity measured using a flat total head tube is not as accurate as an elliptical Pitot static tube, and the flat total head tube has an aperture larger than the value of the theoretical boundary layer thickness, which itself has influenced the flow field.
2) Since the top of the plate is not fully fixed using bolts and can be moved slightly vertically, it is difficult to ensure that the pitot tube probe fits the plate properly at the beginning of the experiment. In actual experiments, the pitot tube has some squeeze on the flat plate, which will cause the measurement of vertical travel distance to be too larger.

Boundary layer type differentiation
I. Curve fitting method
For laminar boundary layer: $\frac{\mathrm{u(y)}}{u_0} \sim \frac{y}{\delta}$

For turbulent boundary layer: $\frac{\mathrm{u(y)}}{u_0} = (\frac{y}{\delta})^{\frac{1}{7}}$, namely, $\ln\left(\frac{\mathrm{u(y)}}{u_0}\right) = \frac{1}{7} * \ln\left(\frac{y}{\delta}\right)$
The boundary layer types were analyzed by examining whether the figure curves follow the above-mentioned relations, and the results are as follows.

Smooth plate

1cm from LE



Data1

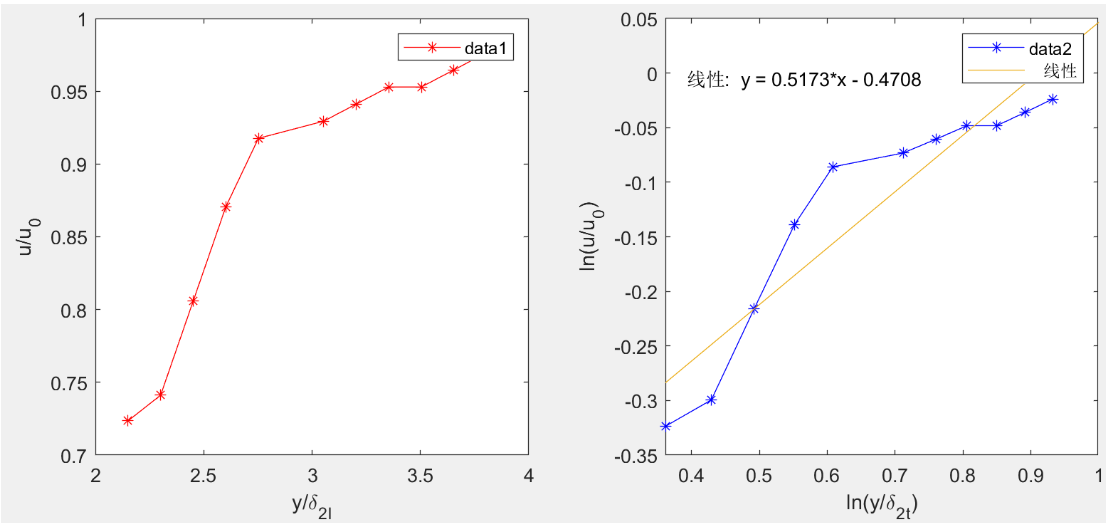
It generally fits this relationship: $\frac{\mathrm{u(y)}}{u_0} \sim \frac{y}{\delta}$

Data2

The coefficient 0.3289 of the fitting result is much bigger than 1/7, so it does not fit this relationship: $\ln\left(\frac{\mathrm{u(y)}}{u_0}\right) = \frac{1}{7} * \ln\left(\frac{y}{\delta}\right)$

Thus it is the laminar boundary layer.

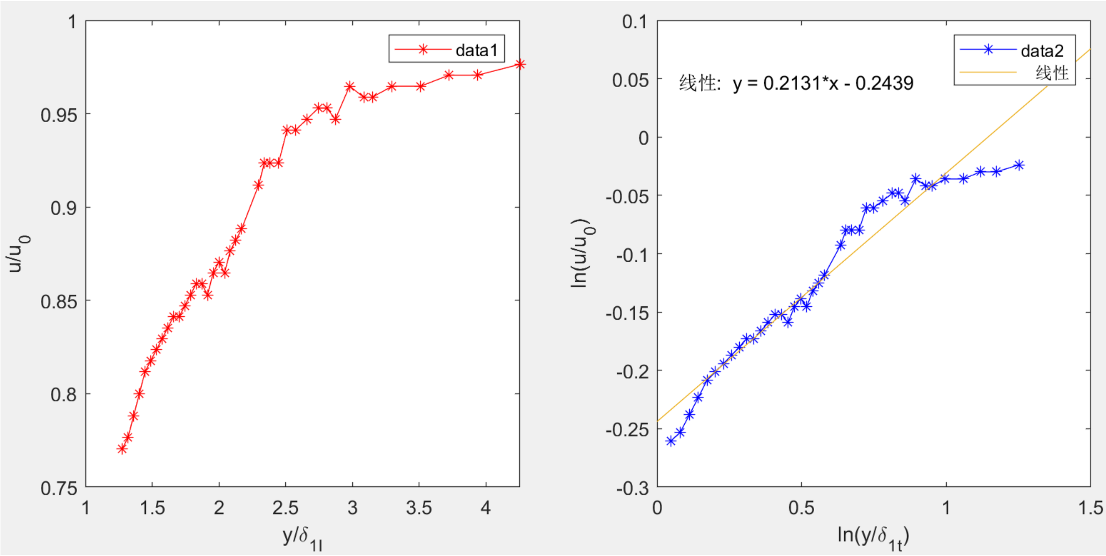
2cm from LE



Through similar analysis, it is the laminar boundary layer.

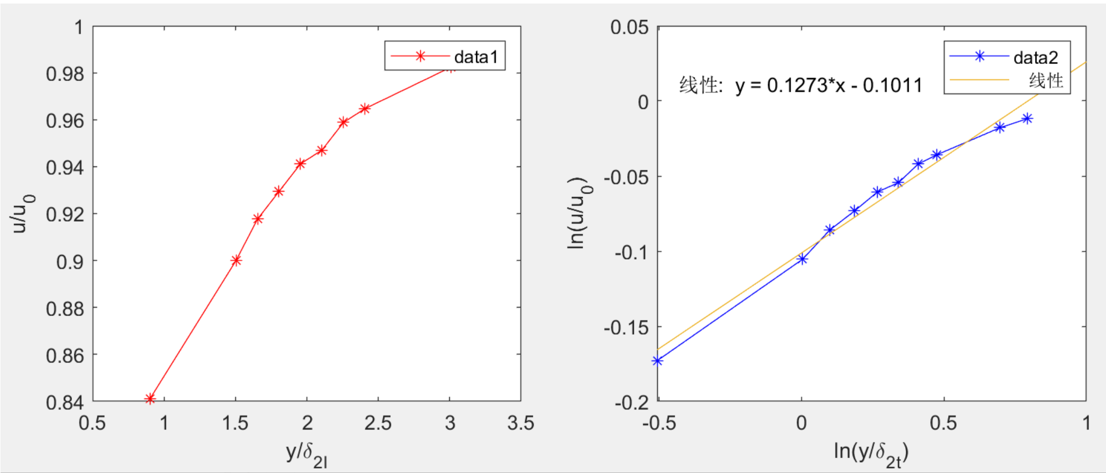
Rough plate

1cm from LE



Through similar analysis, it is the laminar boundary layer.

2cm from LE



Data2

The coefficient of 0.1273 is closer to 1/7.

If the constant term due to measurement error is not considered, it fits this relationship: $\ln\left(\frac{u(y)}{u_0}\right) = \frac{1}{7} * \ln\left(\frac{y}{\delta}\right)$

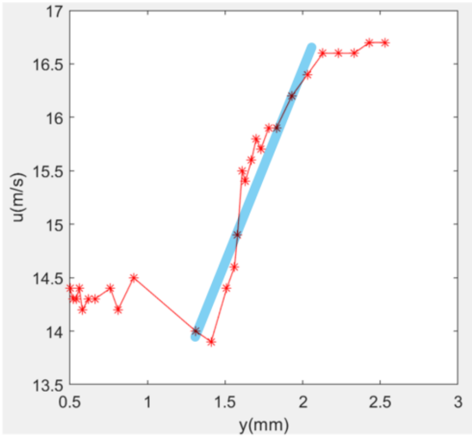
So this is the turbulent boundary layer

II. Plot velocity vs position figure

Due to the large bias in quantitative curve fitting analysis, the following section will analyze the boundary layer type qualitatively by velocity-position figures.

Smooth plate

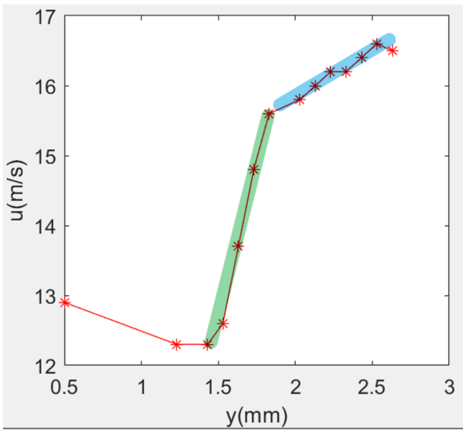
1cm form LE



The velocity distribution is essentially linear with respect to the location,

So it is the laminar boundary layer in this case.

2cm from LE

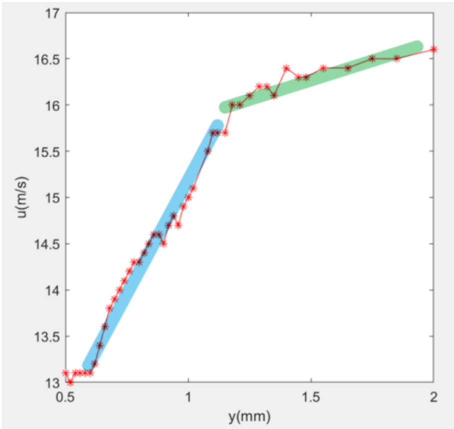


From this figure, it can be noted that the increasement of velocity distribution decreases after about 1.8mm, and it can be judged that it is a laminar flow inner layer (层流内层) before 1.8mm.

Thus it is the turbulent boundary layer.

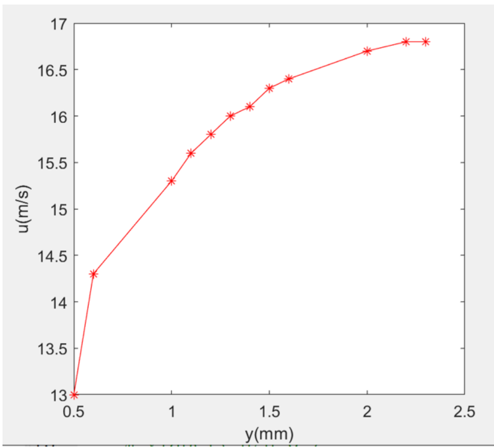
Rough plate

1cm from LE



With two velocity increasement tendency, this velocity distribution is similar to that of the 1cm position in smooth plate case, so it is also a turbulent boundary layer. Compared with the smooth plate, the turbulent boundary layer appears earlier in the rough plate with the same distance from leading edge, the earlier boundary layer transition.

2cm from LE



Since 1 cm position is already the turbulent boundary layer, 2 cm position is also a turbulent boundary layer.

IV. Questions

1.Search for relevant information, combine with the experimental results, analyze what are the factors affecting the thickness of the boundary layer.

1) The distance x from the LE of the plate. The thickness of boundary layer increases with the distance increasing, which has been validated through both theory and experiment.
2) The surface condition of the plate. The experimental results demonstrated that the boundary layer thickness of rough plate is smaller than smooth plate.
3) The characteristic Reynolds number Re_x. According to the formula, the boundary layer thickness is larger with smaller Re_x.
4) The conditions of free stream flow such as density, velocity, viscidity ($since\ Re_x = \frac{\rho x u_0}{\mu}$) and turbulivity.

2.Why is it possible to use only the total pressure Pitot tube when measuring the boundary layer velocity?

In an incompressible flow field, the total pressure at each point is equal to the sum of the static and dynamic pressures at that point.

$$p_0 = p + \frac{1}{2}\rho v^2$$

Then

$$v = \sqrt{\frac{2(p_0 - p)}{\rho}}$$

The static and total pressures need to be measured to calculate the velocity at each point, but considering that the gradient of the static pressure in the direction of the vertical plate is equal to 0 (∂p/∂y=0), we only need to open a static pressure hole on the surface of the plate, and the measured static pressure is the static pressure at all points in the direction normal to the plate where the point is located. In this case, to measure the velocity in the boundary layer, we only need to measure the total pressure at each point along the normal to the plate, thus it is possible to use only the total pressure Pitot tube when measuring the boundary layer velocity.

3.Search for relevant information and discuss the influence of boundary layer on the flow in general.

1) Change of flow velocity. The fluid adhering to the surface of the object, the relative velocity with the surface of the object is equal to zero; from the object side up, the velocity of each layer gradually increases until it is equal to the free flow velocity.
2) Change of flow type. After the development of boundary layer, the flow type can be changed from laminar to turbulent.
3) Change of the thermodynamic properties of the flow. When the object and the gas flow do the high-speed relative motion, in the boundary layer immediately adjacent to the object surface, the temperature and velocity of the gas will be dramatically changed, and often accompanied by the phenomenon of heat and mass exchange. This phenomenon is called mass and heat transfer in boundary layer flow.