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ANALYSIS STUDY OF BOUNDARY LAYER OF AIR FLOWING ON A FLAT PLATE

Sarah Burhan EZZAT[1]

Imam Ja'afar Al-Sadiq University, Iraq

Yousif Khudair ABASS [2]

Imam Ja'afar Al-Sadiq University, Iraq

Qusay Kamil JASIM [3]

Northern Technical University, Iraq

Ahmed E. AHMED [4]

Imam Ja'afar Al-Sadiq University, Iraq

Abstract

When the real liquid flows through a solid object or solid wall, the particles of the liquid stick to the boundary and a non-slip state occurs. In this paper, a practical and theoretical study was conducted to calculate and show the effect of fluid velocity on the thickness of the boundary layer and the local skin friction coefficient and a comparison between the theoretical and experimental results of laminar flow and turbulence along the flat plate at (5,10,15,20, cm). The results showed that the coefficient of skin friction decreases with the increase in the velocity of the liquid and that the velocity increases until it is constant (1m/sec) at the dimension x = 20 cm. The distribution of the velocity, friction coefficient, and thickness of the boundary layer are obtained analytically and experimentally and compared with the previously reported results, where good agreements are observed also the results also showed that there is an error ratio between the theoretical and practical values.

Keywords: Boundary Layer, Local Skin Friction Coefficient, Flat Plate, Momentum Thickness.

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[1] sarah.burhan@saqdiq.edu.iq, https://orcid.org/0000-0003-1544-4838

[2] yousif.khudair@saqdiq.edu.iq, https://orcid.org/0000-0003-0645-5623

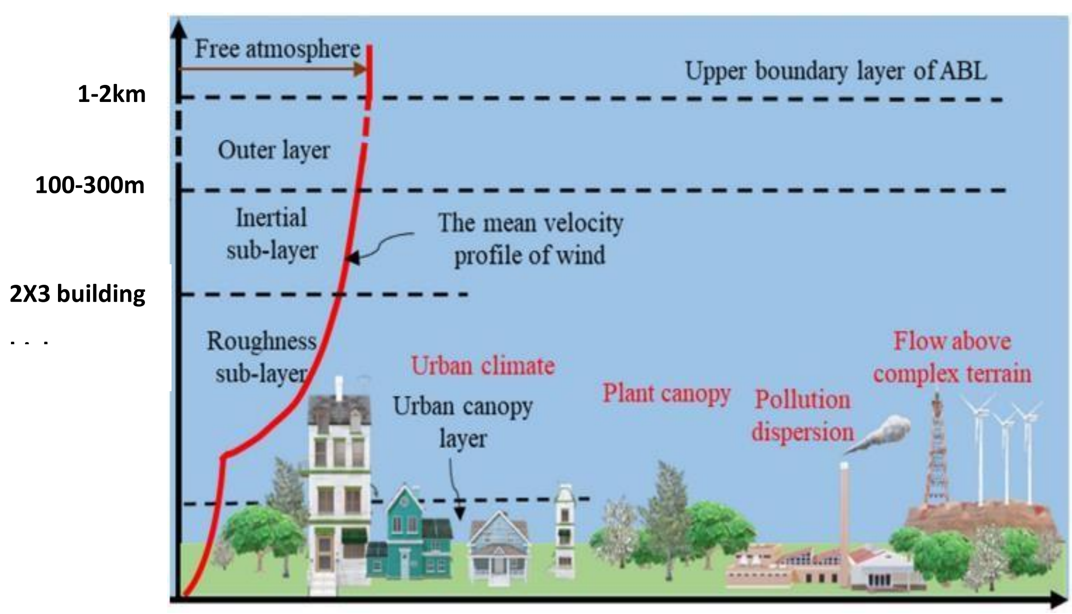
[3] qusay_hwj@ntu.edu.i, https://orcid.org/0000-0003-2189-5301

[4] ahmed.emad@sadiq.edu.iq

Introduction

When considering the flow of a fluid past any object, friction plays an important role. As air passes over the surface, the flow adheres to the surface due to friction between the air and solid material of the plate [1]. The flow velocity iszero at the surface, the no-slip conditions, and therefore near the surface there is a region in which the flow is retarded. This region of the flow that is retarded is called the boundary layer [2]. Dimensionally, the boundary layer is described by the boundary layer thickness. It is the distance from the plate to the point where the flow speed is 99% of the outer flow velocity. A velocity profile, which shows the variation of flow speed with vertical distance from the plate is used to describe the boundary layer. There are two types of boundary layers: laminar and turbulent. The type of boundary layer that will occur depends upon the Reynolds number as well as the surface conditions. The different boundary types have different profiles and different growth rates. Boundary layer theory playing a major rule in aerodynamics (airplanes, rockets, projectiles), hydrodynamics (ships, submarines, torpedoes), transportation (automobiles, trucks, cycles), wind engineering (buildings, bridges, water towers), and ocean engineering (buoys,

breakwaters, cables). The properties of a turbulent boundary layer were investigated related to the drag for a two dimensional fence by K. G. Ranga et.al.[3]. The measurements were obtained at zero pressure gradient of velocity profiles along smooth, rough and transitional flat plates. A simple formula for the displacement thickness and the local shear coefficient has been predicted. This formula was modified to the universal velocity defect law for equilibrium boundary layers. P. Krogstad et.al [4] carried measurements in a zero-pressure-gradient turbulent boundary layer over a mesh-screen rough wall indicate several differences, in both inner and outer regions, in comparison to a smooth-wall boundary layer. The mean velocity distribution indicates that, apart from the expected k-type roughness function shift in the inner region, the strength of the rough-wall outer region 'wake' is larger than on a smooth wall. The Comparison between smooth and rough-wall spectra of the normal velocity fluctuation suggested that the strength of the active motion may depend on the nature of the surface. A. E. Perry et.al. [5].(ABL) flows is another area, where flow over terrain, plant and urban canopies (Fig. 1) act as roughness which influences meteorological and local climate predictions [6-10]. The aim of present work to calculate the boundary layer thickness, local skin friction coefficient and compare between theoretical and experimental results for laminar and turbulent flow along a flat plate.



1-**Theoretical work**

2-1. free stream velocity:

The freestream velocity is defined as the relative velocity in the middle of the blade passage u= 0.995U∞,middle which corresponds to the symmetrical flow approximation.

$$u = \sqrt{\frac{2g \times \rho_w \times h_\infty}{\rho_{air}}} \qquad (1)$$

2-2. Boundary Layer Thickness

for laminar flow over a smooth flat , the exact (or Blasius) numerical solution gives an expression for boundary layer thickness (δ) along the plate in the flow direction , at allocation x from the leading edge, as follows:

$$\frac{\delta}{x} = \frac{4.91}{\sqrt{Re_x}}, \quad For\ Re_x \leq 5 \times 10^5 \qquad (2)$$

For Turbulent Flow:

$$\frac{\delta}{x} = \frac{0.38}{Re_x^{0.2}}, \quad For\ 5 \times 10^5 \leq Re_x \leq 10^7 \qquad (3)$$

2-3. Displacement Thickness

for a laminar flat plate , the numerical (or Blasius) solution gives an expression for displacement thickness (δ^*), asfunction, which is:

$$\frac{\delta^*}{x} = \frac{1.79}{\sqrt{Re_x}} \qquad (4)$$

For Turbulent Flow:

$$\frac{\delta^*}{x} = \frac{0.048}{Re_x^{0.2}} \qquad (5)$$

2-4. Momentum Thickness

Based on the exact (or Blasius) numerical solution the expression of the momentum thickness (θ) along the plate inthe flow dirction,at allocation x from the leading edge, as follows:

for a laminar Flow:

$$\frac{\theta}{x} = \frac{0,664}{\sqrt{Re_x}} \qquad (6)$$

For Turbulent Flow:

$$\frac{\theta}{x} = \frac{0.037}{Re_x^{0.2}} \qquad (7)$$

2-5. Skin friction coefficient and drag force

Based on analysis (Blasius and one-seventh-power law) the local friction coefficient at a location x for laminar andturbulent flow, respectively, over a flat plate was determined as:

$$C_{fx} = \frac{0,664}{\sqrt{Re_x}} \qquad (8)$$

$$C_{fx} = \frac{0.059}{Re_x^{0.2}} \qquad (9)$$

The average Cf determine by integration as:

$$C_f = \frac{1}{L}\int_0^l C_{fx}\, dx \qquad (10)$$

The drag force over the surface is determined as follows:

$$F_D = \frac{1}{2} C_f \, A \rho_{air} U^2 \tag{11}$$

2-6 Shape factor

A shape factor is used in boundary layer flow to determine the nature of the flow. The higher the value of H, the stronger the adverse pressure gradient. A high adverse pressure gradient can greatly reduce the Reynolds number at which transition into turbulence may occur. Conventionally, H = 2.59 (Blasius boundary layer) is typical of laminar flows, while H = 1.3 – 1.4 is typical of turbulent flows. can be calculated as:

$$H = \frac{\delta^*}{\theta} \tag{12}$$

3- Exprimental Rig.

An optional experiment module for use with the (AF10) Air Flow Bench. to study boundary layers on smooth flat plates. Includes a pitot to measure velocity profiles. This module consists of a duct in which there is situated a flat plate as shown in figure(2). The flat plate is rough on one side and smooth on the other, providing different surface conditions for the formation of a boundary layer. In this experiment, the velocity profiles in the boundary layer of a flat plate were measured for a flat plate. In order to discern the type of flow in each case, theoretical approximations for laminar flow and turbulent flow were compared with the experimental values obtained.

Figure(2): Air Flow Bench.

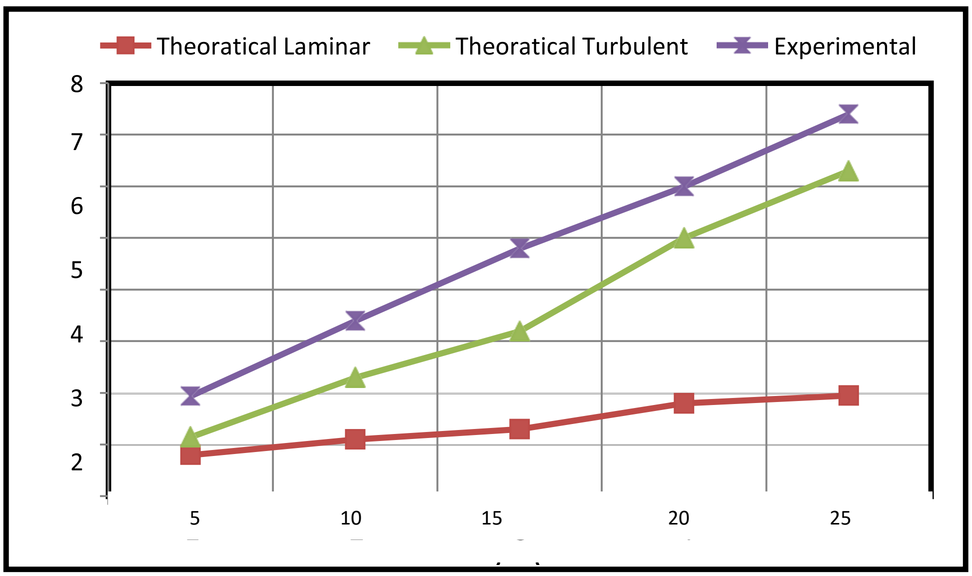
4- Result and discussion.

4-1- Boundary Layer

The method for determining boundary layer thickness was not accurate. So the values of δ and U used for non-local positioning and velocity are not accurate. This may be the source of some differences in both profile and boundary layer thickness values between experimental and theoretical values and this is the reason for the obvious differencein Fig(3).

Table(1): Boundary layer thickness with different positons.

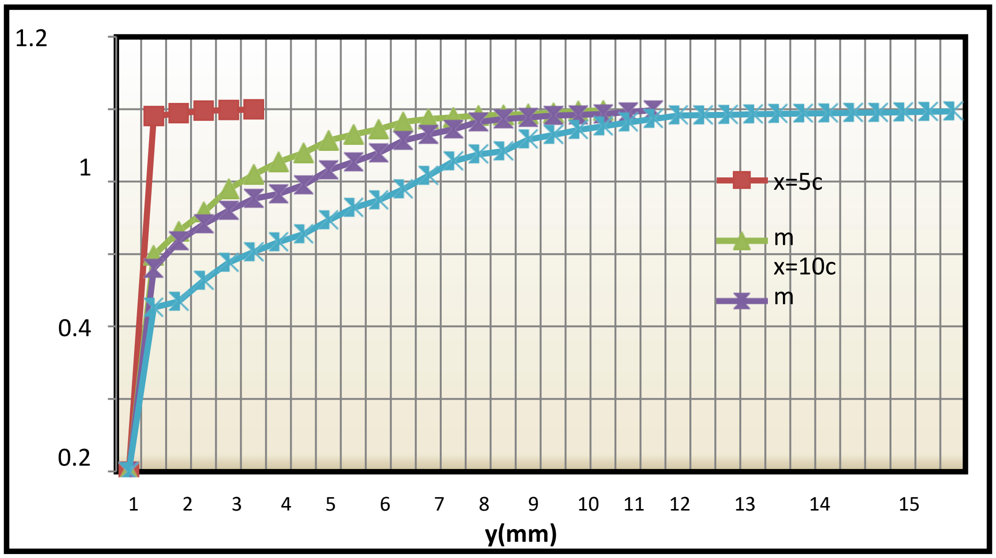
No.	x(cm)	δ(mm)		
		Theoretical Laminar	Theoretical Turbulent	Experimental
1	5	0.8	1.15	1.94
2	10	1.1	2.3	3.4
3	15	1.3	3.2	4.8
4	20	1.8	5	6
5	25	1.95	6.3	7.4



Figure(3): Boundary Layer With Local Position.

4-2 The velocity profile in the boundary layer.

When real fluid flows past a solid body or a solid wall, the fluid particles adhere to the boundary and condition of no slip occurs. This means that the velocity of fluid close to the boundary will be same as that of boundary. If the boundary is stationary, the velocity of fluid at the boundary will be zero. Further away from the boundary, the velocity will be higher and as a result of this variation of velocity, the velocity gradient will exist. The velocity of fluid increases from zero velocity on the stationary boundary to the free stream velocity of the fluid in the direction normal to the boundary. This variation of velocity from zero to free stream velocity in the direction normal to the boundary takes place in a narrow region in the vicinity of solid boundary. The velocity profile in the boundary layer is increase at different locations along the plate as shown in fig(4).



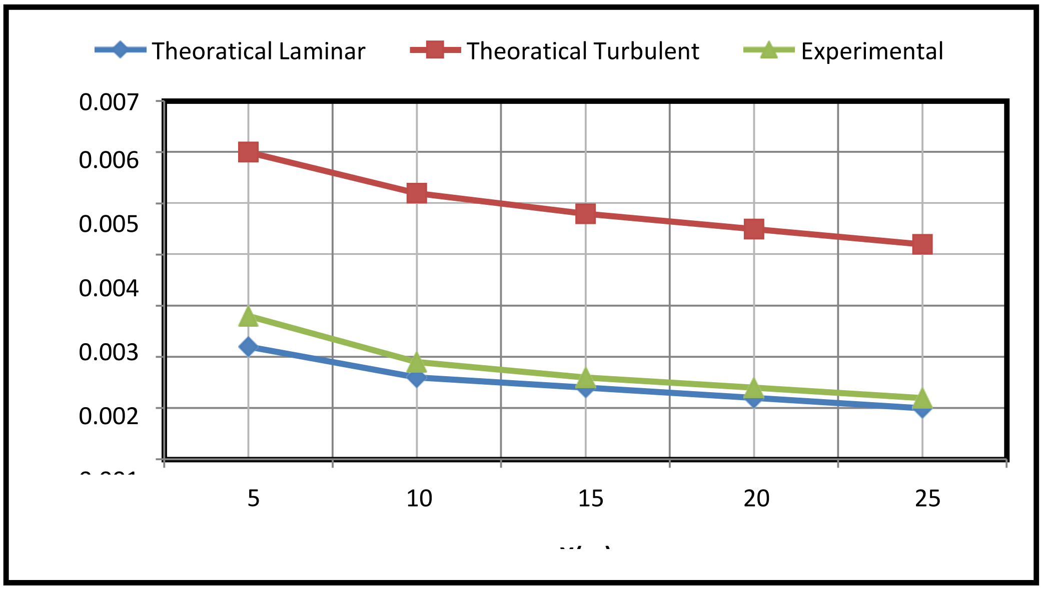
Figure(4): The velocity profile with the boundary layer .

4.3 local friction coefficient.

Table (2) shows the relationship between the coefficient of friction and the local position, Fluids can only exert two types of forces: normal forces due to pressure and tangential forces due to shear stress. Pressure drag is the phenomenon that occurs when a body is oriented perpendicular to the direction of fluid flow. Skin friction drag isthe frictional shear force exerted on a body aligned parallel to the flow, and therefore a direct result of the viscous boundary layer. Due to the greater shear stress at the wall, the skin friction drag is greater for turbulent boundary layers than for laminar ones as shown in fig(5).

Table(2): local friction coefficient with different positons.

No.	x(cm)	C_{fx}		
		Theoretical Laminar	Theoretical Turbulent	Experimental
1	5	0.0022	0.006	0.0028
2	10	0.0016	0.0052	0.0019
3	15	0.0014	0.0048	0.0016
4	20	0.0012	0.0045	0.0014
5	25	0.001	0.0042	0.0012



Figure(5): friction coefficient with Local Position.

Figure 6 also shows a comparison between the results from the current study and those from well-proven equations that were published in the literature by renowned writers. Correlations of Cf=0.074 Re -0.2 introduced by Prandtl [12] , Cf= 0.455[Log(Re)]-2.58, Cf= 0.37[Log(Re)]-2.584 suggested by Schultz and Grunov [13]. It is evident that there is good agreement between the results. Figure 6 shows that by increasing Reynolds number, C f decreases. By applying curve fitting method to the current results, a new formula for be offered as: Cf= 0.045Re -0.16.

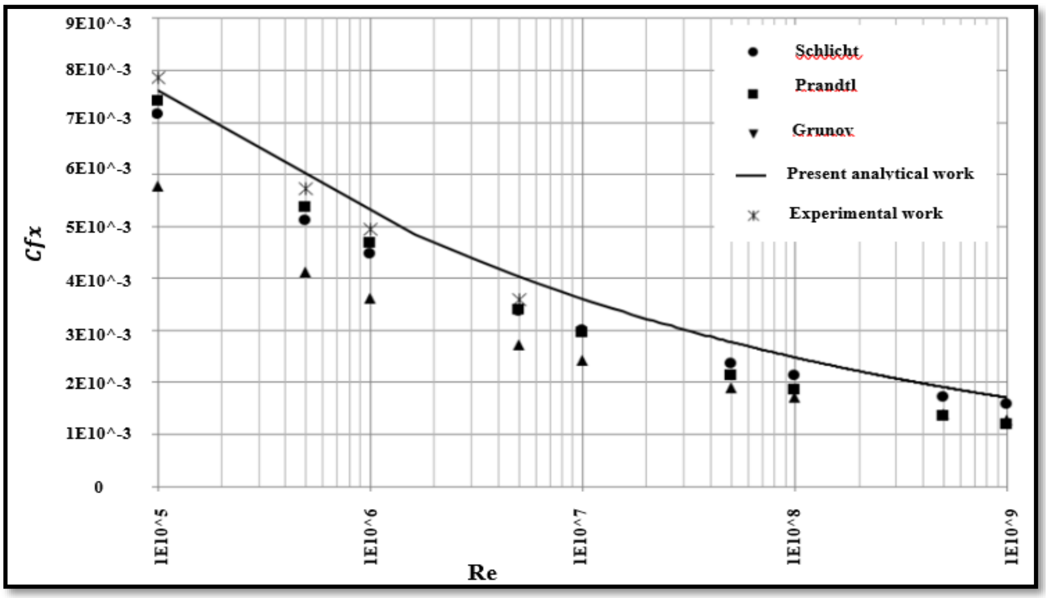
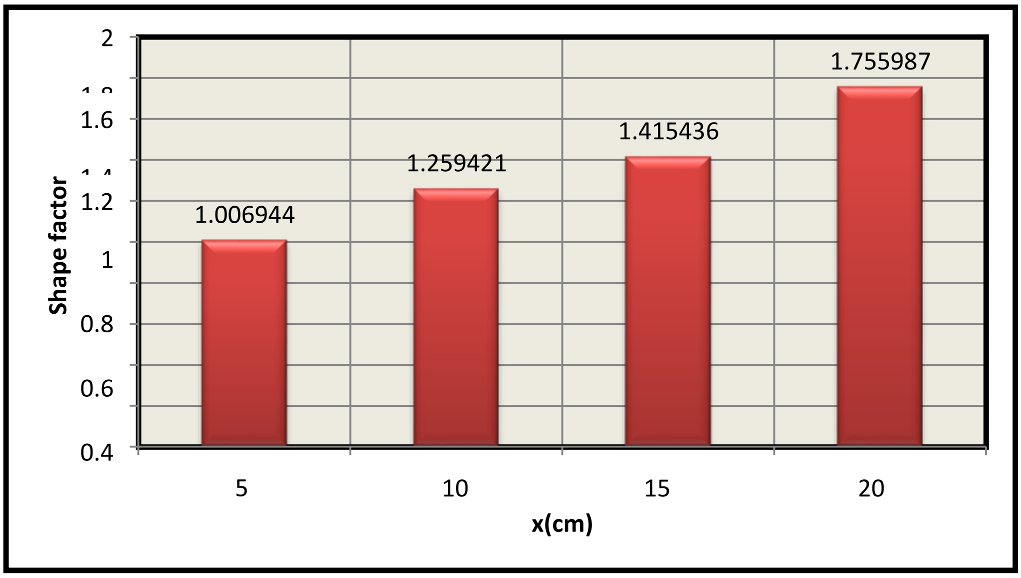


Fig. 6. Comparison results for Cf current analysis with previously reported at different Re.

4-4 Shape factor.

A shape factor is used in boundary layer flow to determine the nature of the flow .The higher the value of H, the stronger the adverse pressure gradient. A high adverse pressure gradient can greatly reduce the Reynolds number at which transition into turbulence may occur as shown in fig(7). Conventionally, H = 2.59 (Blasius -boundary layer) is typical of laminar flows, while H = 1.3 – 1.4 is typical of turbulent flows.



Figure(7):shape factor with local positon.

Conclusion

In conclusion, comparisons made between experimental results and theoretical data allow the determination to be made that the boundary layer over the plate was a laminar boundary layer, and the boundary layer over plate was turbulent.

1. The differences between these two types of boundary layers was clearly demonstrated.
2. The results showed that the coefficient of skin friction decreases with the increase in the velocity of the liquid.
3. the velocity increases until it is constant (1m/sec) at the dimension x = 20 cm.
4. The shape factor of laminar and turbulent flow respectively is 1.259421 , 1.755987.
5. The error between theoretical and experimental for friction coefficient is 6.67%.

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Nomenclature

u	freestream velocity(m/s)	δ^*	Displacement Thickness(mm)
h∞	Height(cm)	C_{fx}	local friction coefficient
$\boldsymbol{\rho}$	Density(Kg/m^3)	F_D	Drag force (N)
g	Gravitational acceleration(m/s^2)	A	Area of the plate(m^2)
Re	Reynolds number	H	Shape factor
δ	Boundary layer thickness(mm)	y	Normal-wall direction
ϴ	Momentum Thickness(mm)	ABL	Atmospheric Boundary Layer
x	Local distance of the plate(cm)		