EXPERIMENTAL AND NUMERICAL CHARACTERIZATION OF TURBULENCE IN FLUID FLOW

BY

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ABSTRACT

This dissertation presents experimental measurements on a round free turbulent jet and numerical simulations on a flow past a surface mounted cylinder. The experimental measurements map the Reynolds stresses in a vertical round free jet. A 12 mm diameter nozzle with exit velocity of 8 m/s with corresponding Reynolds number of 6000 were used to determine the differences in mean velocity profiles, turbulence intensity profiles, and velocity spectra in the flow of a vertical round free jet at room conditions. Constant Temperature Anemometry (CTA) with 1D probe was used to measure the mean and fluctuating velocity components to obtain the Reynolds stress correlations. The results show that different mechanisms may have control in various types jet flows or in different regions of a jet flow. In free jet flows, the downstream region is dominated by turbulence structure whereas coherent eddy-structure can have a strong influence on the near field; particularly for low-Reynolds number jet flows. The present study is an attempt to review the current information on vertical round free turbulent jet flows. The influence of origin of the jet (initial conditions) and the boundary conditions on the jet flow structure is considered. The result depicts that the exit conditions of the jet play a very important role in the development of the jet in the near field but the far field flow remains independent of the exit conditions of the jet. The numerical solution is preform by using large eddy simulations (LES) for the flow around a surface mounted cylinder. Cylinder of height-to-diameter ratios of 2.5 with a thin boundary layer of the approach flow have been analyzed and compared to the available literature using StarCCM+. The detailed study presented confirms largely the flow behavior of the fluid flow comprehensively when the fluid interacts with a bluff (solid) body (cylinder). It also provides further insight and quantitative information on the mean flow, the turbulent fluctuations and the unsteady flow features. The mean-flow behavior is analyzed with the aid of streamlines and contour plots of mean-velocity and fluctuation components. The vortex shedding flow pattern past the cylinder is further analyzed for determining the Reynolds stresses. Alternating shedding is found to occur over the cylinder. The shedding is observed mainly near the ground where it is also mostly alternating but intermittently also symmetrical. The aim of the work is to characterize turbulence in a fluid flow in terms of Reynolds stresses.

خلاصة البحث

هذه الأطروحة تقدم قياسات تجريبية للأضطربات الحرة على منفث مستدير بالاضافة الي محاكاة عددية للتدفق العابر علي سطح اسطوانة .تمت اجراءت القياسات التجريبية لايجاد توزيع اجهادات رينولدز في المحور الرأسي للمنفث المستدير. و تم استخدام فوهة بقطر 12 ملم مع فتحة خروج بسرعة 8 م/ث عند عدد رينولدز مساوً لـ 6000 وذلك لتحديد الاختلافات في توزيع السرعة المتوسطة وشدة الاضطراب وسرعة الأطياف في التدفق العمودي للمنفث المستدير عند ظروف الغرفة. تم استخدم جهاز قياس سرعة الرياح عند درجة حرارة ثابتة (CTA) مع مجس احادي الابعاد لحساب مركبات السرعة المتوسطة و السرعة المتذبذبة للحصول على علاقة اجهاد رينولدز. اظهرت النتائج أن آليات متنوعة قد يمكن استخدامها للتحكم في تدفقات مختلفة أو في مناطق مختلفة من للمنفث المستدير يهيمن الاضطراب في التدفقات الحرة على منطقة المصب في حين ان الدوامة المتماسكة يمكن أن يكون لها تأثير قوي في المناطق القريبة، خاصة عند تدفقات أعداد رينولدز القليلة .هذه الدراسة هي محاولة لإعادة النظر في المعلومات الحالية عن الأضطربات الحرة للمنفث المستدير. تم اخذ تأثير الظروف الأولية للطائرة وشروط الحدود على هيكل التدفق بعين الاعتبار.واظهرت النتائج أن شروط الخروج من المنفث تؤثر في تطوير المجال القريب، ولكن يظل تدفق المجال البعيد مستقل عن ظروف مخرج المنفث. تمت دراسة المحاكاة العددية باستخدام دوامة كبيرة للتدفق حول سطح مركبة اسطوانية. وقد تم تحليل اسطوانة بنسبة طول إلى قطر مساوً 2.5 داخل تدفق بطبقة حدود رقيقة ومقارنتها باستخدام برنامج.+ StarCCM النتائج التفصيلية لهذه للدراسة تؤكد إلى حد كبير أن سلوك تدفق السوائل يكون بشكل شامل عندما يتفاعل السائل مع جسم صلب (اسطوانة), كما أدت النتائج الي القاء الضو علي التدفق المتوسط و الاضطرابات المتذبذبة وخصائص التدفق الغير مستقر.خصائص التدفق المتوسطة تم تحليلها بمساعدة الخطوط الانسيابية وخطوط شكل السرعة المتوسطة و المركبة المتذبذبة للتدفق. كذلك تم تحليل نمط تدفق الدوامة بعد عبور الاسطوانة لتحديد اجهادات رينولدز.أظهرت النتائج تدفق دوامات فوق الاسطوانة وتقل شدتها بمسافتها بوجود تناوب متماثل فوق الاسطوانة بالقرب من سطح الأرض. والهدف من هذا العمل هو وصف الاضطرابات في تدفق السوائل من حيث الضغوط رينولدز.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion; it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Mechanical Engineering.

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, expect where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Jalal Mohammed Zayan

Signature:………………………..   Date:………………………..

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To Almighty Allah for means; and my beloved family and friends for support.....

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LIST OF ABBREVIATIONS

CTA	Constant Temperature Anemometry
CFD	Computational Fluid Dynamics
PIV	Particle Induced Velocimetry
LDA	Laser Doppler Anemometry
RANS	Reynolds Averaged Navier-Stokes Equation
SHW	Stationary hotwire
DNS	Direct Numerical simulation
LES	Large Eddy Simulation
RMS	Root mean Square
NIF	Near and intermediate field

LIST OF SYMBOLS

Re	Reynolds Number
ReD	Reynolds number based on diameter: ReD = UD/ν
St	Strouhal number
T	Temperature (^{o}C)
f	Frequency(Hz)
G	Acceleration due to Gravity
x,r,θ	Polar co-originates
$r_{1/2}$	Jet half radius: $Ur_{1/2}$ = Uc/2
u,v,w	Velocity components, m/s
u',v',w'	Fluctuating velocity components in x,y and z direction.
U, V, W	Mean velocity components
Uj	Axial mean velocity at the nozzle exit
Uc	Axial mean velocity at the jet centerline
Nu	Nusselt number
Pr	Prandtl number
V	Velocity (ms−1)

Greek symbols

α	Biot number
µ	Dynamic viscosity (Ns/m^2)
η	Viscosity (kg m^{-1} s^{-1})
ν	Kinematic viscosity (m^2 s^{-1})

CHAPTER ONE
INTRODUCTION

1.1 BACKGROUND

Turbulence in fluid flow is a very complex and also an interesting phenomenon which has captivated the imagination of Engineers and Physicists from all over the world ever since the conceptualization of modern science. The turbulence problem is far from solved, whether in terms of mathematical and intuitive understanding, or in terms of characterization of turbulence. A fundamental understanding and characterization of turbulence is very essential because it will help to solve many engineering problems related to fluid flow and also in the control of turbulence itself. This research is an effort to characterize the turbulence field in the flow past a surface mounted cylinder.

1.2 TURBULENCE IN FLOW OF FLUIDS

The phenomenon of turbulence can be found almost anywhere and everywhere in every field of life, starting from the wind in the atmosphere to stirring of a coffee cup. The flow of rivers and wind is generally turbulent, even if the currents are very gentle. The air or water swirls and eddies while its overall bulk moves along a specific direction. Almost all industrial, man-made flows are turbulent. And also all naturally occurring flows on earth, in oceans, and atmosphere are turbulent. Most practical flows occurring in engineering applications involve non-homogeneous turbulent flows that are affected by boundaries or body forces. Some of the examples of a turbulent flows include jet streams in the upper troposphere, currents below the surface of the oceans, strong cumulus clouds and deep turbulent convection in the ocean, the boundary layer in the earth's atmosphere, boundary layers growing on propellers and aircraft wings, combustion processes, mixing in turbulent chambers, wakes of cars, ships, aircrafts and submarines, blood flow in arteries, oil transport in pipelines, lava flow, the flow through pumps and turbines etc.

From a scientific perspective, turbulent flows are complex to understand but also at the same time, they are fascinating even after many decades of research. The drawbacks of many numerical simulations and uncertainty of the results obtained through all these years of research on turbulent flows, serve as additional information for many more researches to be conducted to provide a better understanding of the concept of turbulence itself. The main aim of the study of turbulence research is to understand the concept of turbulence in real time in the fluid flow and its structure. It is very important to know that turbulence is not a feature of fluids but of fluid flow, in which the fluid undergoes irregular fluctuations compared to a laminar flow which is the motion of fluids in layers and of smooth paths. In turbulent flow the velocity of the fluid at a point is continuously undergoing changes in both magnitude and direction. Tennekes and Lumley (1972) proposed a list of some basic characteristics of turbulent flows:

- Irregularity or randomness: Turbulent flow is always unpredictable. Thus a deterministic approach has to be employed to study the problem of turbulence by relying on numerical and experimental methods.
- Diffusivity: This is a property of turbulence, which causes rapid mixing and increased rates of momentum, heat, and mass transfer and makes it an important feature in turbulent flows. This property is useful for many applications. It prevents boundary-layer separation on airfoils at large angles of attack, increases heat transfer

rates in machinery of all kinds. It is the source of the resistance of flow in pipelines, and it increases momentum transfer between winds and ocean currents. If a flow does not exhibit spreading of velocity fluctuations through the surrounding fluid but pattern looks random, then the flow is surely not turbulent. In a case of aircraft jet contrails, excluding the turbulent region just behind the aircraft, the contrails have a very nearly constant diameter for several miles. Such a flow is not turbulent, even though it was turbulent when it was generated.

- Reynolds number: Turbulent flows always occur at high ($Re > 5x10^5$ for flows past flat plate) Reynolds numbers. It often originates as instability of laminar flows if the Reynolds number becomes too large. The instabilities are related to the interaction of viscous terms and nonlinear inertia terms in the equations of motion. This interaction is very complex. Randomness and nonlinearity combine to make the equations of turbulence nearly intractable. Thus this situation makes turbulence research a very challenging. It is one of the principal unsolved problems in physics even today after many decades of research.
- Three-dimensional vorticity fluctuations: Turbulence is rotational and three dimensional. It is characterized by high levels of fluctuating vorticity. Hence, vorticity dynamics plays an essential role in the description of turbulent flows. If the velocity fluctuations were two dimensional, the random vorticity fluctuations that characterize turbulence could not maintain themselves. Flows that are substantially two dimensional, such as the cyclones in the atmosphere which determine the weather, are not turbulent themselves, even though their characteristics may be influenced strongly by small-scale turbulence, which interacts with the large-scale flow. For example, random waves on the surface of oceans are not in turbulent motion since they are essentially irrotational.

- Dissipation: turbulent flows are always dissipative. Viscous shear stresses perform deformation work which increases the internal energy of the fluid at the expense of kinetic energy of the turbulence. Turbulence needs a continuous supply of energy to make up for these viscous losses. If the energy supply is stopped, turbulence of the flow decays rapidly. Random motions, such as gravity waves in planetary atmospheres and random sound waves (acoustic noise), have insignificant viscous losses and, therefore, are not turbulent. The major distinction between random waves and turbulence is that waves are essentially non dissipative, while turbulence is essentially dissipative.
- Continuum: turbulence is a continuum phenomenon, governed by equations of fluid mechanics. Even the smallest scales occurring in a turbulent flow are ordinarily far larger than any molecular length scale.
- Property of Flows: Turbulence is a feature of fluid flows and not of fluids. The dynamics of turbulence is almost the same in all fluids, whether they are liquids or gases, provided the flow has a high Reynolds number. Since the equations of motion are nonlinear, each individual flow pattern has certain unique characteristics that are associated with its initial and boundary conditions. No general solution to the Navier-Stokes equations is known; consequently, no general solutions to problems in turbulent flow are available. Since every flow is different, it follows that every turbulent flow is different, even though all turbulent flows have many characteristics in common.

The above discussed properties are the characteristics of turbulence. Turbulence study is broadly classified into three categories Experimental, analytical and numerical simulations. In our research, we study the characteristics of turbulence experimentally and through numerical simulations. In this work, experimental investigation of a round free turbulent jet and numerical simulation of a three-dimensional flow past a surface mounted bluff body (cylinder) will be carried out in order to get a better understanding of turbulence.

1.3 FLOW PAST A BLUFF BODY

A bluff body is a body of certain volume which obstructs flow of a fluid in a particular direction. The flow of fluid over the bluff body generates aerodynamic forces, skin friction drag, a wake region behind the body and vortex shedding in the wake region. The size, intensity and interaction of the vortex system varies substantially based on factors like the Reynolds number, aspect ratio of the body, surface roughness of the body and proximity to the mounting surface. A proper experimental/numerical study of these vortex patterns may provide an insight into the nature of turbulence itself. Therefore in this work, the bluff body is modelled as a cylinder and mounted on a flat surface. Numerical simulations are carried out to observe the flow behavior in close proximity of the cylinder. The choice of a cylinder as a bluff body has been made due to the fact that cylinder-like structures can be found in many engineering applications, such as heat exchangers, cooling systems for nuclear power plants, offshore structures, buildings, chimney stacks, overhead power transmission lines, undersea cables and pipe lines. Such a configuration complicates the fluid flow dramatically.

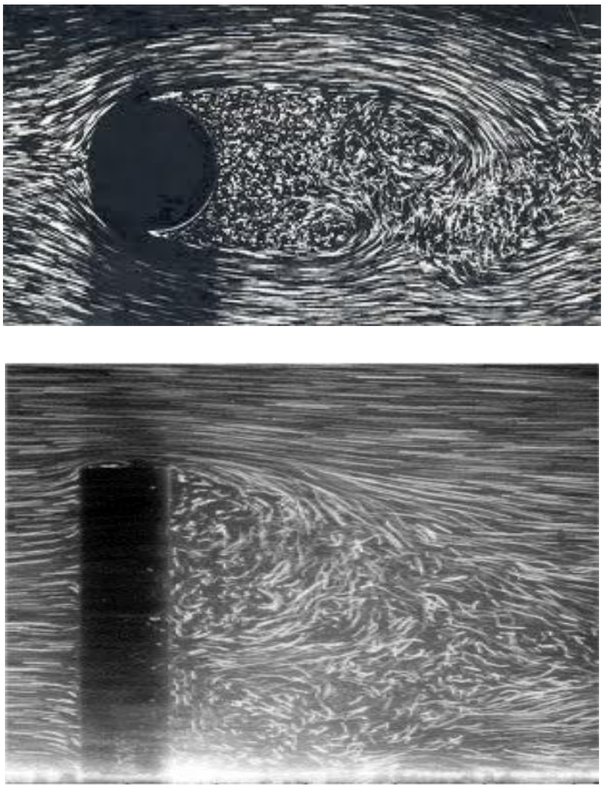

Figure 01.1: Flow visualization of a flow past a surface mounted cylinder: (a) top view and (b) side view (Afgan et al, 2006)

When the fluid flows over a bluff body (cylinder), a series of disturbances occur in the flow along the direction of the flow around the cylinder. When the flow reaches the bottom of the cylinder, it deflects along the surface of the cylinder causing counter rotation of currents known as vortices on all sides of the cylinder. A down flow is developed due to the downward negative stagnation pressure gradient of the non-uniform approach flow adjacent to the upstream face of the cylinder. The interactions between the bottom edge flow and the horizontal boundary layer separation close to surface results in the formation of a vortex system. The two ends of this vortex system are swept downstream by the flow as they wrap around the cylinder in the shape of a horseshoe in plain view and hence popularly known as the horseshoe vortex. Horseshoe vortex is created at the intersection of the cylinder with the mounting plane which is often not steady in terms of its location and size. At the top, free end of the finite cylinder, a complex three-dimensional flow is formed. The flow climbs the cylinder and when it passes, it forms a series of vortices at the edge.

In order to map these vortical structures and to visualize them, some of the techniques like Smoke-wire visualization, Constant Temperature Anemometry (CTA), Particle induced velocimetry (PIV) Laser Doppler Anemometry (LDA), Laser Doppler Velocimetry (LDV) surface pressure measurement and numerical simulations using any commercial software can be employed to study the effects on the surface of cylinder on the laminar and turbulent junction flows. The above mentioned methods are mainly used to measure the turbulence quantities like mean velocity components, fluctuating velocity components and Reynolds stress components of the flow. Mapping and understanding the Reynolds stress components in a flow are of high importance in the study of turbulence as it might give some new insight into the physical mechanisms responsible for the vortex shedding. Hence engineers and scientist are developing many methods to find the Reynolds stress components in a flow by using both experimental and numerical methods. By using Reynolds stress components, we may obtain a better or complete understanding of the characteristic and the mechanisms which is responsible for the creation of turbulence in the fluid flow.

1.4 REYNOLDS STRESSES

The fundamental objective of most researches in field of turbulence is to ultimately explain the nature of the transport process. Turbulent shear flow in these transport processes tends to explain the physical meaning of Reynolds stresses. The Reynolds stresses are the mean forces (per unit area) imposed on the mean flow by turbulent fluctuations. They arise from the nonlinear advection term when the Navier–Stokes