UNIVERSITI PUTRA MALAYSIA

MEASUREMENT OF DIFFERENT OBSTACLES EFFECT ON RECTANGULAR CAVITY IN LOW REYNOLDS NUMBER FLOW FIELD USING PARTICLE IMAGE VELOCIMETRY

AHSAN NUR MUBARAK ZAHARI @ ANNUAR

FK 2013 91

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By

AHSAN NUR MUBARAK ZAHARI @ ANNUAR

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia, In Fulfilment of the Requirement for the Degree of Master of Science

June 2013

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DEDICATIONS

to both of my parents Zahari @ Annuar Bin Yahya and Che Mahani Bt. Tengku Ibrahim
to my lovely wife Nen Hasbeyah Bt. Mohamed Izazi
to my son Izz Walee Mahdi B. Ahsan Nur Mubarak

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Master of Science

MEASUREMENT OF DIFFERENT OBSTACLES EFFECT ON RECTANGULAR CAVITY IN LOW REYNOLDS NUMBER FLOW FIELD USING PARTICLE IMAGE VELOCIMETRY

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AHSAN NUR MUBARAK ZAHARI @ ANNUAR

June 2013

Chairman : Azmin Shakrine Bin Mohd Rafie, PhD

Faculty : Engineering

Flow past a cavity is a topic of great interest in the field of fluid dynamic properties. The characteristics of the flow depend on the Reynolds number, types of boundary layer, Mach number and the geometry of the cavity itself. Even though a large amount of investigation has been instigated for various objectives and aspects of the flow, the properties of dynamic flow involving cavities have yet to be fully discovered.

Review of literature leads to the need of investigation about the effect of an obstacle in front of a rectangular cavity. The cavity can be explained as a two-dimensional body that would disturb the flow from upstream to downstream which mathematically defined as loss of forces in momentum equation. The lost forces can be described as drag which can give a significant effect in terms of flow dynamic problem. By introducing an obstacle, the idea is to control the flow from entering into the cavity which is the main reason of cavity drag creation.

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The purpose of this current experiment was to investigate the effect of six different types of obstacle at the leading edge of a rectangular cavity in upstream laminar flow condition with $Re_L = 5.12 \times 10^4$. The characterization also included the changes of cavity depth with respect to cavity length (*L/D* = 4, 2.29, and 1.78) and freestream velocity within a very low speed region (*V* = 3.8 m/s, 4.8 m/s, and 6.5 m/s). The findings of this current experimental result will be used in the development of predicting fluid behaviour inside the cavity associated with this flow field.

The experiment was conducted in an open subsonic wind tunnel designed purposely for low speed regions. The data was obtained by using 2-D Particle Image Velocimetry (PIV). The test model was designed using transparent materials for both flow visualization and allowing the laser sheet to pass through in experiments, acquiring 700 image pairs for each individual experiment resulting in an overall velocity vector.

The result was produced using a mean velocity profile that was separated into *u* and *v* components. Analysis of the data showed that the obstacle affected the flow inside and above the cavity. Changing the obstacle type also changes the strength of vortex occurrence within the cavity with the triangle obstacle of 1 cm width and rectangular obstacle of 1 cm width generated the best flow behaviour among obstacles for differentiating the cavity depth and velocity within low Reynolds number region. The significance of result can be used as a foundation result for further investigation to any type of cavity with obstacles research.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

PENGUKURAN UNTUK KESAN PENGHALANG YANG BERBEZA KEPADA ALIRAN NOMBOR REYNOLDS YANG RENDAH PADA KAVITI SEGIEMPAT TEPAT MENGGUNAKAN ALAT UKUR KELAJUAN GAMBAR BERPATIKEL

Oleh

AHSAN NUR MUBARAK BIN ZAHARI @ ANNUAR

Jun 2013

Pengerusi : Azmin Shakrine Bin Mohd Rafie, PhD

Fakulti : Kejuruteraan

Aliran udara melalui sebuah rongga atau kaviti ialah salah satu topik yang sangat penting untuk penyelidikan dinamik bendalir. Ciri-ciri aliran bergantung kepada nombor Reynolds, jenis-jenis lapisan sempadan, nombor Mach dan geometri rongga itu sendiri. Walaupun sejumlah besar siasatan telah dijalankan untuk pelbagai matlamat dan aspek-aspek bagi aliran, ciri-ciri aliran dinamik melibatkan rongga belum lagi sepenuhnya diterokai.

Tujuan eksperimen yang terbaru ini ialah untuk menyiasat kesan aliran udara di dalam rongga berbentuk segiempat tepat apabila diletakkan enam jenis penahan di hadapan rongga segi empat tepat dalam keadaan aliran lamina dengan $Re_L = 5.12 \times 10^4$. Pembolehubah adalah perubahan kedalaman rongga segiempat tepat ini terhadap panjang rongga (*L/D* = 4, 2.29 , dan 1.78) dan halaju luar dengan kelajuan yang sangat rendah (*V* = 3.8 m/s, 4.8 m/s , dan 6.5 m/s). Hasil keputusan eksperimen

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terkini ini akan digunakan sebagai asas ramalan tingkah laku aliran bendalir di dalam rongga dengan berpandukan keadaan aliran yang berkaitan.

Eksperimen dijalankan di dalam satu terowong angin subsonik yang terbuka yang dikhaskan untuk rantau kelajuan yang perlahan. Data telah diperolehi dengan menggunakan 2-D Alat Ukur Kelajuan Gambar Berpatikel (PIV). Model untuk eksperimen dihasilkan dengan menggunakan bahan lutsinar untuk visualisasi aliran dan membenarkan pancaran cahaya laser melaluinya, dan cubaan sebanyak 700 gambar berpasangan-pasangan dilakukan untuk setiap eksperimen berasingan menghasilkan satu vektor halaju.

Keputusan dibuat berdasarkan profil halaju purata dengan cara menghuraikan halaju komponen *u* and *v*. Analisis data menunjukkan bahawa penahan memberi kesan terhadap aliran di dalam dan di atas rongga. Perubahan jenis penahan juga menghasilkan pusaran aliran yang mempunyai kekuatan berbeza-beza dalam rongga dengan penahan segitiga dengan kelebaran 1 cm dan segiempat tepat dengan kelebaran 1 cm menghasilkan aliran terbaik berbanding penahan-penahan yang lain apabila diubah kedalaman kaviti dan halaju dalam rantau kelajuan perlahan.

`

ACKNOWLEDGEMENT

Thank you to The Almighty, Allah S.W.T for giving me the strength and passion to complete this thesis

I would like to express my gratitude to my supervisor Dr. Azmin Shakrine Mohd Rafie for his brilliant guidance and patient in the completion of this thesis. I would like to thank Dr. Mohamed Thariq Hameed Sultan and Prof. Ir. Dr. Shahnor Basri for their help and useful opinions throughout my research work. My experimental work would not be completed without the help from Mr. Ropiee Mat and Mr. Saffairus Saleh, our hardworking and superb technician. I would like to thank them for the priceless lesson and precious time for this research and life.

I am forever in debt to my dear parents. Thank you for your limitless support.

`

I certify that a Thesis Examination Committee has met on 3rd June 2013 to conduct the final examination of Ahsan Nur Mubarak bin Zahari @ Annuar on his thesis entitled “Measurement of Different Obstacles Effect on Rectangular Cavity in Low Reynolds Number Flow Field Using Particle Image Velocimetry” in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The committee recommends that the student be awarded the Master of Science.

Members of the Thesis Examination Committee were as follows:

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been properly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution. Intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012; Written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012. There is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

AHSAN NUR MUBARAK ZAHARI @ ANNUAR

Date: 3 June 2013

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LIST OF NOMENCLATURES

Symbols

L	Length	m
h	height	m
d	Depth	m
f	frequency	s^{-1}
u	Streamwise velocity	m/s
v	Normal velocity	m/s
$\overline{uv}$	Mean momentum transfer	
$\overline{u'v'}$	Reynolds Stress	
Ma	Mach number	
Re	Reynolds number	
V	Freestream velocity	m/s
$\langle u \rangle$	Mean streamwise velocity	m/s
$\langle v \rangle$	Mean normal velocity	m/s
L/D	Length-to-depth ratio of cavity	
x	Streamwise distance	m
y	Vertical distance	m

Greek

θ	Momentum thickness	m
ρ	Density	kg/m^3
$\mu\left(\frac{\partial \bar{u}}{\partial y}\right)$	Viscous Stress	
Π	Pi	

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Γ	Circulation	

Subscript

h	height/depth of cavity	m
L	Length of cavity	m
d	depth of cavity	m
e	excitation of frequency	
s	shear stress	

Abbreviations

PIV	Particle Image Velocimetry
CFD	Computational Fluid Dynamics
RANS	Reynolds Averaged Navier Stokes
WB	Cavity without obstacle
TRI1	Cavity with 1 cm length of triangle obstacle
REC1	Cavity with 1 cm length of rectangular obstacle
HC1	Cavity with 1 cm length of half-cylinder obstacle
TRI2	Cavity with 2 cm length of triangle obstacle
REC2	Cavity with 2 cm length of rectangular obstacle
HC2	Cavity with 2 cm length of half-cylinder obstacle

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CHAPTER 1

INTRODUCTION

Transportation is one of the most common topics among researchers. Air, land, and water transportation have unlimited potential for progress to achieve an optimum design for maximum benefit. Improving fuel consumption is one of the highlights for recent research aside from rate of performance for certain transport such as aircraft, cars, and others.

Many aspects need to be observed like the types of transport, the shape, power consumption and many more but one of the problem factors that all transportation face is the flow dynamics problem. Developing a new transportation design that can reduce fuel consumption and drag is one of the chosen criteria. According to Bertin (2002), flow control can save fuel by around 27 – 30 % for aircraft. It was well noted how important it is to get the best flow control for any kind of transportation.

All transportation must face the flow dynamics problem whether on solid surface like on land or fluid such as air and water. The mechanism is different but the effect is quite the same for aerodynamics or hydrodynamics. Even though there are advantages and disadvantages for the effect of flow, but for some reason, the flow must be controlled to get what is needed most. All designers and aircraft engineers

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aim to build the fastest and the most fuel efficient design. One of the answers is lying in this current research.

Flow dynamics problem always occur on the surface region. There must be some imperfections on the surface that are known as surface irregularities. Most surface irregularities are caused by manufacturing or design constraints for different vehicles. They cannot be removed completely but only can be adjusted to get the best aerodynamic effect. In flight for example, these include landing gear wells, weapon bays, and other aircraft grooves. Meanwhile, for land or water transport, these include sunroof window, side window, gap between truck and its body, and many more applications. These surface irregularities will increase the defection of flow and all of those surface irregularities can be described as cavity.

1.1 Introduction of Cavity

Since the early 1930's, the study of flow regarding with cavity had been investigated worldwide. As mentioned by Hoerner (1965), the investigation of any surface irregularities were highly recommended as to reduce overall drag or fuel consumption for achieving new development in the transportation industry especially for aircraft.

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According to McGregor and White (1970), a cavity can be described as anything that looks like a gap, cut-out, notch, or groove on the surface that has both borders at its leading and trailing edge. In early investigations on cavities, researchers realised that although the geometry of a cavity was simple, the complexity of flow behaviour inside a cavity was tremendously difficult to understand because it not only depended on the shape of the cavity but also on the upstream approaching types of flow, variation in speed, and boundary layer. As concluded by Gaudet and Winter (1973), it is unlikely to produce a simple analysis method for describing the possible combinations of flow pattern inside a hole (cavity) because of its complexity.

A cavity can cause many effects that need to be understood deeply further which generates wanted and unwanted flow behaviour in real applications. Although most of the cavity effects are considered as bad factors, some other applications look the other way round. The easiest example for using the advantages of cavity effects is a vortex generator. Kuethe and Chow (1986) mentioned that vortex generators are used as a tool to reduce flow separation on airfoils by increasing the flow attachment on the surface. One type of vortex generator is called a cavity vortex generator and among the famous institutions that are involved with cavity effect is NASA for the supersonic flow region as reported by Hazlewood (1996).

(a) Boat Sunroof

(b) Car Sunroof

(c) Car Window

(d) Landing Gear Well

(e) Weapon Bay

(f) Doors and Windows for Train

Figure 1.1 Examples of cavity on vehicles

Another consideration for the cavity effect is to reduce flow disturbance inside or shear layer effect on the cavity. The flow will tend to enter the cavity which creates vorticity flow. The vorticity will give some effect on increasing drag, acoustic problems and others. For these disadvantages, researchers intend to control the flow

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inside the cavity to reduce the occurrence of vortices which is the area of study of the current research.

From the general information, knowing the importance and the behaviour of flow inside a cavity is essential to design the best aircraft or any vehicles. Many researchers understand these perfectly and give their effort pushing to their limit to gather as much information about it as possible. They have been going detail by detail in each part and component which is meaningless to people who cannot understand the beauty of aerodynamics.

1.2 Problem Statement

Since the earliest development in researching cavity problems in fluid mechanics, the main focus has been already identified which is to reduce the drag as much as possible. Many kinds of ways have been conducted even as today. All of them tried to push the limit to reduce the vortices inside a cavity. The main goal, which has not changed to this day, is to increase the performance of aircraft or other vehicle to its maximum. There are many ways to increase the performance of aircraft, and they are willing to investigate parts by parts, region by region as thoroughly as possible. One of the regions is cavities.

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As discussed earlier in this chapter, the cavity effect can increase drag by disturbance of flow within the cavity. From the fundamental aerodynamics theory for an application of the momentum equation in terms of drag of a two-dimensional body, the forces on the control volume are considered by two contributions, the pressure distribution over the control volume surface and the presence of a body within the volume. The cavity can be visualized as a body within the control volume that would disturb the downstream flow which can be described as a loss of force. The loss of force is called drag. It is well known technique that drag can be calculated with wake survey based on momentum principle. This mechanism can be seen clearer in Figure 1.2.

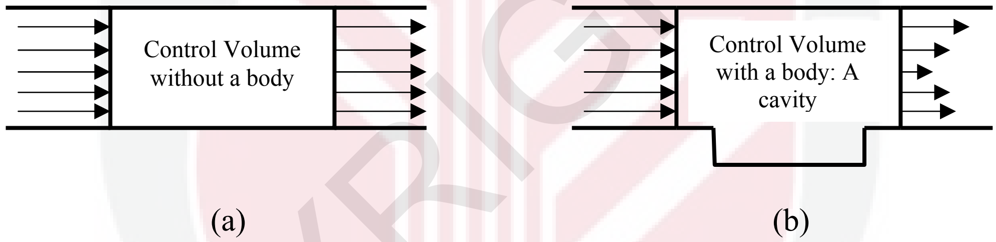

Figure 1.2 Control volume for obtaining drag on a two-dimensional body

Studying the cavity is sufficient to increase the performance of aircraft or other vehicles. The principle also has been used by Roshko as a control volume inside the cavity. According to Gharib and Roshko (1987), the term 'drag of the cavity' was used to explain the situation as shown in Figure 1.3 and the connection of drag in terms of cavity effect can be obtained by integrating mean momentum flux and turbulent shear layer on the cavity.

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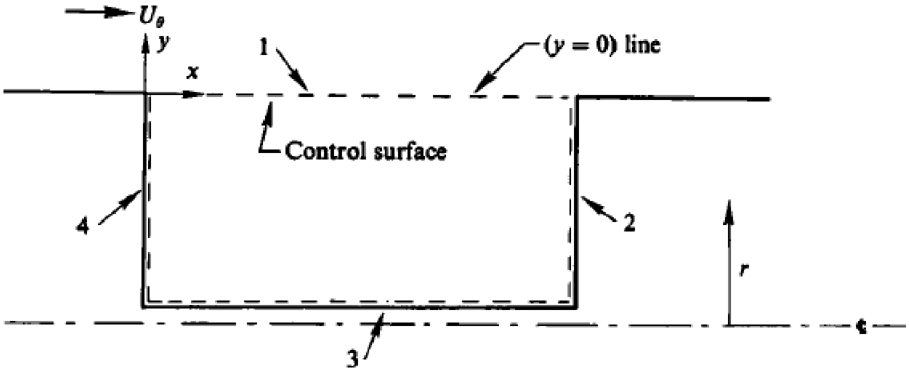

Figure 1.3 Schematics of the cavity
(Source: M. Gharib and A. Roshko,1987)

Cavity drag was created more on momentum flux and shear layer effect and this can be investigated basically by using flow velocity field as mentioned by Gharib and Roshko (1987) to get the assumption of vortex occurrence and strength in the cavity. Even though a cavity is always related to increasing of drag, some research also has the opposite opinion which is that cavities can help the performance of an aircraft wing in certain conditions by reducing separation wake flow as the flow in the cavity can enhance the performance of airfoils at certain angles of attack.

For real applications as shown in Figure 1.1, there was an obstacle in front of the cavity like at a car window, train and none for an aircraft weapon bay. These obstacles are already there and seem to have positive effects on the cavity flow or may be able to produce some kind of flow control mechanism for the cavity as suggested by Rossiter (1964).

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Therefore, an experiment was made to establish the effect of obstacle on the cavity flow as a form of passive flow control with the limitation of low Reynolds number and upstream laminar flow region. The pressure will not be investigated for this experiment, observing only the changes of velocity field inside the cavity related to the prediction of vortices behaviour.

1.3 Objectives

Generally, the objective was to investigate flow behaviour in the rectangular cavity by using a Particle Image Velocimetry (PIV) measurement system. Specific objectives for the current research work were made to comply with the problem statement previously. The objectives are as follows:

a) To investigate the effect of rectangular cavity depth for *L/D* = 4, 2.29 and 1.78 by flow velocity around 4.8m/s with corresponding Reynolds number, Re_L = 5.12 x 10^4 based on cavity length.

b) To investigate the effect of obstacles at the leading edge of rectangular cavity of *L/D* = 4, 2.29 and 1.78 by flow velocity around 4.8m/s.

c) To investigate the effect of different speed at 3.8 m/s, 4.8 m/s and 6.5 m/s for rectangular cavity with *L/D* = 4.

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1.4 Scope of Study and Relevance

The scope of study for this research is the effect of a cavity as one of the surface irregularities on the body in terms of flow behaviour. The current work involves six different of obstacles at the leading edge of the cavity with different depths. The existence of a cavity on the surface, also referred to as cut-out surface, will change the flow pattern on the surface and allow the flow to go through inside the cavity which can enhance the effect. Therefore, passive flow control has been used by putting the obstacle that will perturb the incoming flow and reduce the possibility of vortices creation inside the cavity.

The existence of obstacles in front of cavity-like surfaces on vehicles is very common especially for cars, trucks, trains and motorboats. Doors and windows on vehicles are always designed with an obstacle-like shape in front, and the tops of trucks also have an obstacle-like design but the need in having the best obstacle and to understand deeper about the effect of existing obstacle in front of the cavity is a requirement to enhance the performance of those vehicles.

Currently, there is no information regarding of the effect of obstacle in terms of a rectangular shallow cavity effect with very low Reynolds number. Hence, this research will focus on its effect by using present techniques and approach of flow characteristic experiment. The configuration of cavity design for the current research

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was a rectangular shape with differing length-to-depth ratios (*L/D*) of 4, 2.29 and 1.78.

The cavity Reynolds number was set at approximately 5.12 x 10^4 based on cavity length while the speed involved is 4.8 m/s. These design parameters were taken into consideration based on literature from previous work done by other researchers in this field of study like Grace *et al.* (2004). Another two speeds were involved for *L/D* = 4 without obstacle just to strengthen the result. These speeds were 3.8 m/s and 6.5 m/s as to compare different speed in the same region of very low Reynolds number.

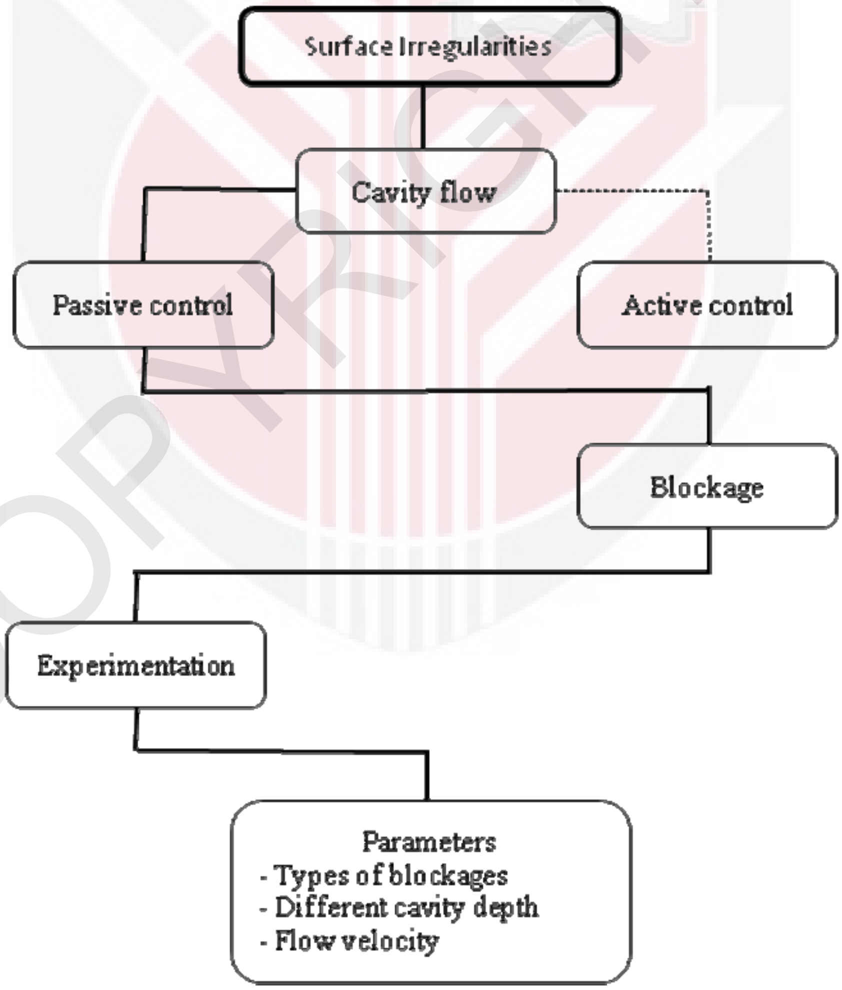

Figure 1.3 Scope of study

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For obstacle parameters, there was no information from previous researchers during the period of study. Thus, the parameters had been decided by using logical assumptions based on how to control the flow going inside the cavity and to reduce the flow separation because of the obstacle itself. The experiment involved specifically only on flow visualization and the data was based on *u* and *v*-velocity profile, nothing mentioned on pressure distribution, noise problems and any other data. These are the limitations and the scope of study for the current research work. Figure 1.3 above illustrates the summary for the scope of study.

1.5 Hypothesis

The main objective for the research was to investigate the effect of varying obstacles at the leading edge of cavity such as a triangle or half-cylinder shape on flow behaviour inside the cavity. Hypothetically, by having an obstacle in front of the cavity, the flow will be disturbed which can reduce the possibility of vortex formation inside the cavity. Rossiter (1964) suggested that adding a small spoiler can suppress the magnitude of periodic pressure fluctuation for a cavity with L/D = 1. From this information, logically, any disturbance that is located in front of a cavity will prevent the flow to come inside. The larger the obstacle, the lesser the flow would go inside the cavity but it must not be large enough as to reduce any increasing drag force outside the cavity.

This research also investigated several cavity depths with and without obstacle at the leading edge. As a hypothesis, the depth of cavity also affects the flow behaviour

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inside the cavity and will change for any result in each obstacle. These results will enhance the conclusion for each obstacle case regarding two main variables, which are obstacle and cavity depth.

This work also tested the effect of speed for one selected cavity depth without obstacle. Making minor changes in speed, the prediction is that this would not have any obvious effect on the flow inside the cavity. However, the empirical data must be taken before any conclusion is made.

1.6 Thesis Layout

This section describes the thesis layout. There are five chapters involved for this investigation, including Chapter 1, which is this introduction. Chapter 2 involves previous research and the state of the art of this work. Chapter 3 provides the details about the experimental methodology. Chapter 4 shows the results and discussion and Chapter 5 summarizes the result.

In Chapter 1, there would be a general information of the importance of current research work which covers a brief history for the cavity investigation and the requirement needed. Real application also included as a breafing knowledge of usage about cavity. The problem statement and objectives were included to emphasis the current work.

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Chapter 2 is the literature review section of the thesis. Prior research that has been done regarding cavities were summarized into several topics. Types of cavities that have been observed and some explainations about them have been introduced briefly. The justification of presenting the current work has been included in this chapter.

For Chapter 3, the methodology which was employed in the experiment and processing data is discussed. All the processes and experimental setup involved in developing the current research has been described thoroughly. The method for obtaining and processing the data from Particle Image Velocimetry (PIV) is explained step by step. The uncertainty analysis is included later in this chapter.

Chapter 4 is the main emphasis of the thesis which gathers all the data involved in the experiments. The results that had been taken from the experimental process were analyzed, presented, and discussed in detail. The data was the summarization of velocity field data obtained from PIV and had been interpreted in graphs for certain sections. Comparisons had been made for all obstacles and different *L/D*.

Chapter 5 provides the conclusion of the results and the limitations involved in the project. Future work recomendations were made and proposed based on the empirical results that had been previously discussed in proper.

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