COMPUTATIONAL FLUID DYNAMICS OF URINARY CATHETERIZATION

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MAY 2018

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfillment of the requirement to graduate with honors degrees in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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(FARAH AISYAH BINTI NAZRY)

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ACKNOWLEDGEMENT

First of foremost, I would like to give a special gratitude to my supervisor, Dr. Mohd Sharizal Abdul Aziz for his guidance and help throughout the whole project. I am thankful for all the contribution in stimulating suggestions and encouragement, helped me to coordinate my project which enables me to carry out the analysis more smoothly especially in writing this report.

Furthermore I would also like to acknowledge with much appreciation to my classmates because they had been helping me with this project from day one so that I can finish this project in time.

Next, I would also like to express my utmost gratitude to all the lectures and technical staffs in the School of Mechanical Engineering, Universiti Sains Malaysia for sharing their knowledge on their area of expertise and gave permission to use all the required equipment and necessary materials to make my progress run more smoothly.

Nevertheless, I express my gratitude toward my family and friends for their kind co-operation and moral support throughout the completion of the whole project and thesis.

Title of thesis: **Computational Fluid Dynamics of Urinary Catheterization**
Date of submission (Academic year): **23 May 2018**
Candidate (Matrix no.): **Farah Aisyah Binti Nazry (125012)**
Name of supervisor: **Dr. Mohd Sharizal Abdul Aziz**

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NOMENCLATURE & ACRONYMS

In this section the nomenclature and acronyms used in the report are listed with the correspondent International System (IS) units.

Nomenclature

Re	Reynolds number
V	Velocity (m/s)
ν	Kinematic Viscosity (m^2/s)
ρ	Density of fluid (kg/m^3)
μ	Dynamic Viscosity (Pa·s)
y^+	Dimensionless vector first node distance from the wall
1D	Mono-dimensional
2D	Two-dimensional
3D	Three-dimensional

Acronyms

CAUTIs	Catheters Urinary Tract Infections
CFD	Computational fluid dynamics
SI	International system units
UI	Urinary Incontinence
CAD	Computer-aided Design

ABSTRAK

Perkomputeran Dinamik Bendalir untuk Pengkateteran Urinari

Pengkateteran urinari ialah satu tatacara perubatan yang digunakan untuk mengeluarkan air kencing dari pundi kencing khas buat pesakit yang menghidapi masalah untuk kencing secara semulajadi. Tiub kencing ialah sebuah tiub fleksibel berongga yang mengeluarkan cecair dari pundi kencing dan dikumpulkan di dalam beg saliran.Terdapat banyak komplikasi yang dihadapi oleh para pesakit, contohnya seperti jangkitan saluran kencing,kekejangan pundi kencing,kebocoran,darahan di dalam tiub kencing dan batu karang. Maka, simulasi ini dijalankan adalah untuk menentukan diameter and konfigurasi terbaik untuk mengoptimumkan kadar aliran jisim menggunakan Perkomputeran Dinamik Bendalir menggunakan perisian ANSYS Fluent. Untuk mengajuk ciri ciri air kencing,air digunakan sebagai cecair bagi simulasi ini kerana ciri ciri air menyerupai ciri ciri air kencing. Objectif simulasi ini adalah untuk menyiasat kesan perubahan diameter dan konfigurasi kepada tiub kencing dan mengoptimakan kadar aliran jisim pada cecair (air kencing). Daripada lima jenis konfigurasi, konfigurasi berbentuk ‘L’ telah menunjukkan kadar aliran jisim dan kecerunan tekanan yang paling optima.Parameter-parameter ini akan membantu dalam mengelakkan pembentukan bakteria berlaku pada permukaan tiub kencing.Seterusnya,menggunakan konfigurasi berbentuk ‘L’, lima diameter berlainan digunakan dalam simulasi untuk mencari diameter paling relevan untuk penggunaan pesakit. Melalui semua simulasi, tiub kencing berdiameter CH18 dalam konfigurasi berbentuk ‘L’ menunjukkan hasil yang paling baik. Kesimpulannya, pemahaman parameter yang penting untuk dijadikan kayu ukur penggunaan tiub kencing yang selamat dan sihat amatlah penting untuk rujukan pada masa hadapan.

ABSTRACT

Computational Fluid Dynamic for Urinary Catheterization.

Urethral catheterization is a medical procedure that helps the drainage of urinary bladder for patients that have difficulties urinating naturally.An urinary catheter is a flexible tube that collects urine from human bladders, straight to the drainage bag. There are many complications faced by the patients such as urinary tract infections (UTIs) ,bladder spasms,leakage,blood in catheter tube and bladder stones.Thus,this project will determine the best diameter and configuration of the catheter to optimize the mass flow rate using Computational Fluid Dynamic (CFD) in ANSYS Fluent software.To mimic the characteristics of urine,instead of using water as fluid (water has the closest characteristic as urine).The objectives of this simulation are tto investigate the effect of diameters and configuration of urinary catheter tube in urinary catheterization system using Computational Fluid Dynamics (CFD) technique and to optimize the diameter and configuration of the urinary catheter tube.From five different configurations, an L-shaped configuration showed the best mass flow rate and pressure gradient. This parameters will help in preventing any encrustration happening on the wall of catheter. Subsequently, from this configuration, five different cases that represented five different diameters were then simulated to find the most releven diameter for human usage. From all the simulations a catheter with diameter CH18 in an L-shaped configuration showed the best result possible. In conclusion, understanding the parameters for a safe and healthy usage of urinary catheter are important for future application.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter is discussed about the project background, the probem of the project, the objectives of the project and the project scope.

1.2 Project Background

Urethral catheterization is a medical procedure that helps the drainage of urinary bladder for patients that have difficulties urinating naturally.An urinary catheter is a flexible tube that collects urine from human bladders, straight to the drainage bag[1].Urinary catheter comes in three different types which are indwelling catheter, intermittent catheter and suprapubic catheter[2]. Figure 1 shows the example of each type of catheters. Urinary catheters come in many sizes and types. They can be made of silicone,rubber or plastic such as PVC[3]. Figure 2 illustrates the miscellaneous diameters of urinary catheter. However ,there are many complications faced by the patients such as urinary tract infections (UTIs) ,bladder spasms,leakage,blood in catheter tube and bladder stones[4].A study by McGrother et al in the year 2004 shows that in United Kingdom, more than 9 millions people where one third of them are 40 years old, are affected by the urinary storage symptoms and more than 5 millions of them required healthcare[5]. Thus,this project will determine the best diameter and configuration of the catheter to optimize the mass flow rate using Computational Fluid Dynamics (CFD) using ANSYS Fluent software.To mimic the characteristics of urine, water is used as fluid (water has the closest characteristic as urine)[6]. The main geometrical characteristic of a catheter is its diameter. Catheters are in fact labeled by their size units, which are called French (FR) or Charrière (CH) where 1 CH= 1/3 mm. Figure 3 simplify the conversion of urinary catheter from French Size to Milimeter(mm) Size. The bigger the diameter the faster the urine will flow from the bladder and hence reducing the voiding period. However a larger diameter means an increase difficulty in the insertion with the possibility of urethral trauma[7]. The mass flow rate of the urine through the catheter is an indication of the time spent to complete this operation. An increase in the mass flow rate, for a

defined size catheter, means consequently less time spent for this operation increasing the satisfaction of the patient. This literature imposed constraints to the analysis of the urinary catheter to ensure that a compromise between optimal flow, patient's comfort, and everyday practicality. As a result a total of two design parameter characteristics were examined. The input variables in question are the optimal diameter of the tube and the configuration of the tube.Due to the high number of possible input combinations,a structured approach to the analysis of data was necessary. Therefore,CFD is the best simulation software to simulate the fluid flow inside the catheter .

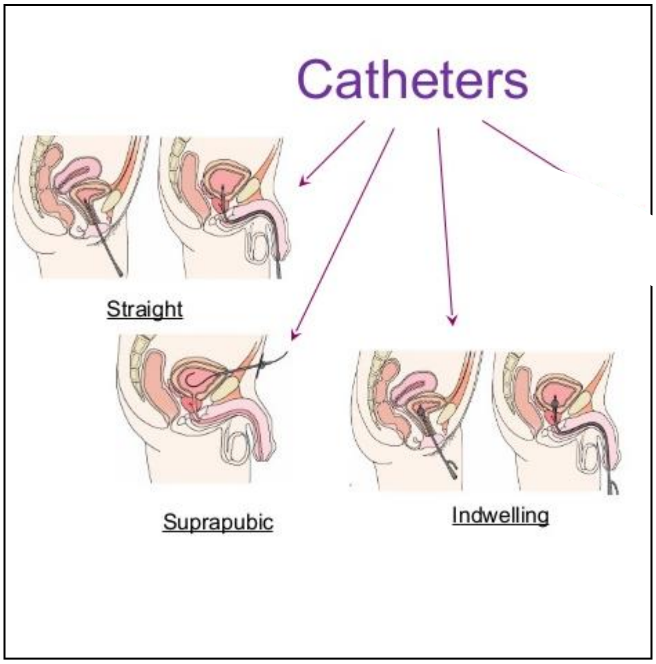

Figure 2.1: Three main types of urinary catheters.

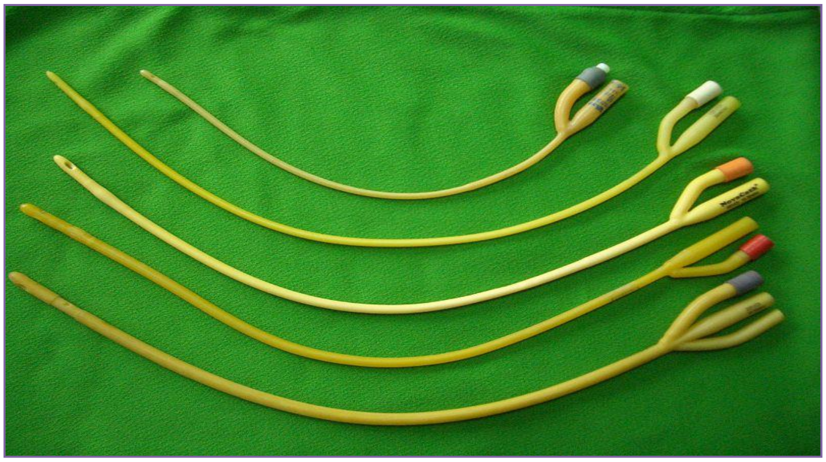

Figure 1.2: Dissimilar diameters of urinary catheters exists in the market.

Foley's Color Code

COLOR	SIZE FRENCH	SIZE MILLIMETER
orange	6	2.0
red	8	2.7
yellow	10	3.3
white	12	4.0
green	14	4.7
orange	16	5.3
red	18	6.0
yellow	20	6.7
purple	22	7.3
blue	24	8.0
black	26	8.7

Figure 1.3: Urinary catheters measured in French Size and translated in milimeter (mm) Size.

1.3 Problem Statement

Patients often suffer some infections due to the unsuitable diameters of catheters being used to empty their bladders.This is called Catheter-Associated Urinary Tract Infections (CAUTIs) and it is caused by the bacterial growth that adheres on the surface of catheters. Others experience discomforts due to backflow of urine and urethral false passages. This can be associated with the configuration of the catheter while being used on the patient.The topic discussed in this paper has a very limited literature focussing on the impact of diameter and configuration of the tube. Therefore, the main objective of this paper is to stimulate the flow in the catheters using CFD. Five different diameters for silicon-coated latex catheter and five different configurations of catheters will be used to obtain the optimized mass flow rate of the urine to avoid any infections and discomforts for the patients.

1.4 Objectives

The objectives of this study are :

1) To investigate the effect of diameters and configuration of urinary catheter tube in urinary catheterization system using Computational Fluid Dynamics (CFD) technique.
2) To predict mass flow rate and pressure inside the catheter tube.

1.5 Project Scopes

From this paper, the flow of urine is simulated inside the catheter tube due to five different diameters of catheters in five different configuration to find the most optimized mass flow rate of urine.Also, we will get to see stress and deformation of the tube that may lead to to blockage of the tube and ultimately trying to avoid this problem. To get to this, using CFD seems like the best approach to use to obtain the optimal value of diameter and the configuration for optimizing the fluid’s flow rate.

CHAPTER 2

Literature Review

2.1 Introduction

This chapter will provide the review from previous researches that are related to this final year project. It includes an introduction of Foley catheter, a few previous researches on materials for urinary catheter,biofilm formation process and current catheter design .This is disscuss as an introductory for all the reseachers done before in the past.

2.2 Foley Urinary Catheter

Almost 100 million catheters are sold everywhere in whole wide world every year and in the United Kingdom, more than 130000 urinary catheters are used per annum [7]. By this, 3 million people are affected economically[8]. Foley indwelling urinary catheter is most commonly used device among all catheters. This system comprises a tube inserted through the urethra, held in place by an inflatable balloon and connected to a drainage system.The catheter is composed of a tube (usually 220-420 mm in length) which an inlet chanel for a saline solution that fills the balloon and outlet chanel for the urine.Figure 2.1 shows two eyelets in rounded rectangular shape from which the urine drains near tips.

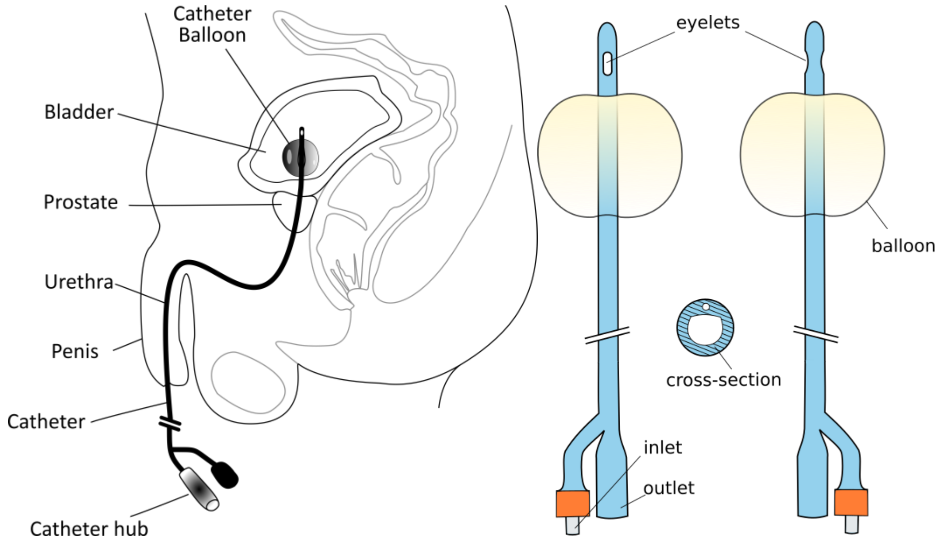

Figure 2.1 :A male (females are similarly affected to males) urinary tract with catheter in place on the left side and the catheter design on the right. The water from the inlet through the little tube fills the balloon which is just below the two eyelets. The picture shows also a cross section which includes a small circular tube and a bigger semi-spherical one which correspond respectively to the inlet and the outlet.

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2.3 Materials of Catheter

For over than 70 years since Foley catheter has existed but infection and discomfort problems still occur to the patients despite the approaches of changing materials and coatings are introduced. The materials used is from Latex to plastic such as PVC and lastly silicone. Range of coating developed are silver,hydrogel,PTFE and different other combination[1]. Based on experiments and findings ,all silicone devices and silver coatings had shown a degree of success. Figure 4 elucidates the groundbreaking approches taken by researches to counter the problem associated with urinary catheters.

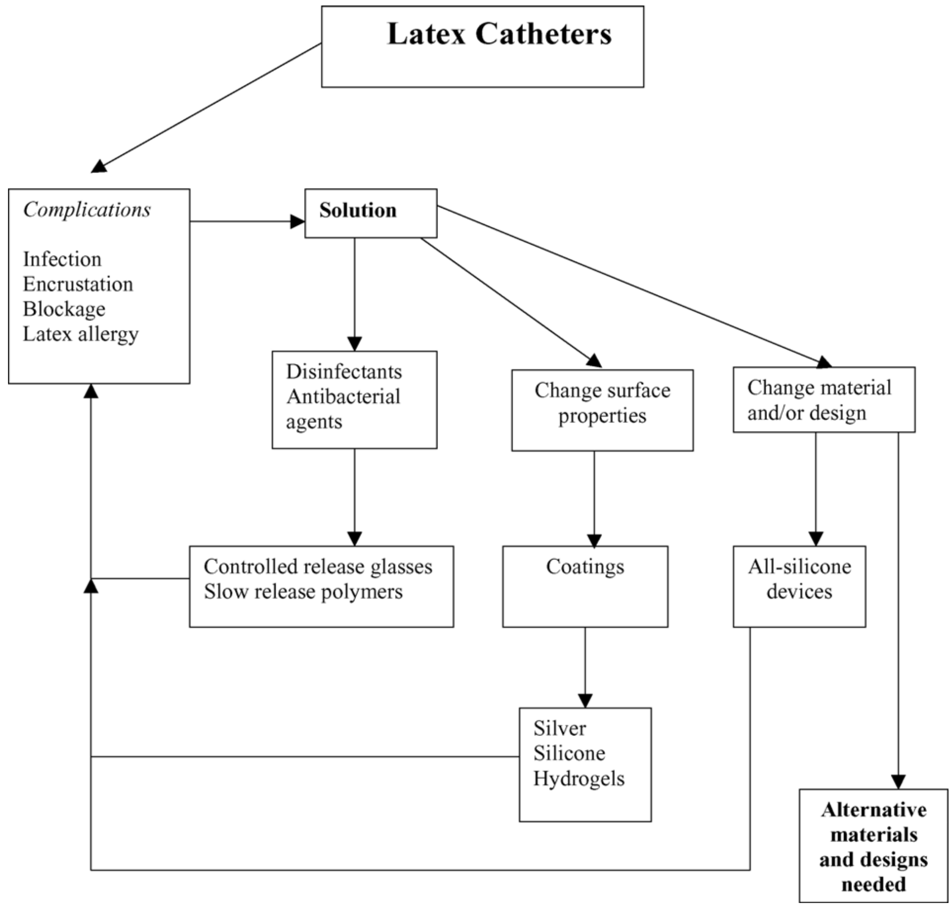


Figure 2.2:Flowchart showing the alternative approaches taken to counter the problems related to urinary catheter.

2.4 Biofilm formation process

The biofilm formation process is made by a microorganism community which grows on the surface of catheter [9]. This colonisation phenomenon can occur not only in many different natural environments but also in infectious diseases [10,11].Henrici et.al [12] had written a paper in 1933 that represent the first ever recorded observation of biofilm phenomenon. Biofilm was defined as a "*protected mode of growth that allows cells to survive in hostile environments and also disperse to colonise new niches"*, and best be described as a dynamically complex and structured biological system, rather than a simply a passive aggregation of cells attached to the surface.

This biolfilm formation to CAUTI's is a biological process that can be subvided in eight steps. This process is related to the length of time which the catheter is kept in place,and it is dependent on chemical and physical factors combined with the enviromental changes, flow properties and catheter design. Also, it is dependent on flow rate,nutrient content and temperature [13]. The first step is (a) the protein adsorption (i.e. adhesion of atoms, ions or larger particles to a surface) on the biomaterial and it is followed by (b) the development of an organic conditioning film on the catheter surface. Once the film is formed, (c) the urease-producing bacteria adhere to the biofilm and (d) a community of bacteria starts to develop biofilm within a bacterial exopolysaccharide matrix. At this point, (e) the pH rise become a crucial factor [14] and (f) calcium and magnesium ions start to bind with the matrix gel. The crystals (g) are then stabilized and can grow and aggregate (h). The process is facilitated by the alkaline urine (pH 8.3-8.6) combined with bacteria attached to the surface [15].

Figure 2.3. Biofilm process inside the Urinary Indwelling Catheter. The key point is the rise of pH which determines calcium and magnesium ions deposition.

The type of bacteria involved in the process of CAUTis is an important aspect. R.C.L Fenelyet.al[16] and D.J Stickler et.al[17] have been been analysing the issue for the last 35 years from a medical, biological and experimental point of view. Their studies showed that the rise in pH to alkaline conditions (pH 8.3-8.6) is almost exclusively due to bacteria *P. Mirabilis, Proteus Vulgaris* and *Providencia Rettgeri*. High values of pH helps the development of biofilm which briefly encrust and blocks the catheter.Tenke et al. [18] demostrated that the rise of pH due to P.Mirabilis is six to ten times faster than the rate caused by other species. Thus, preventing a raise in pH levels is important to reduce catheter encrustation as shown by experimental studies[19].

2.5 Current catheter designs

Designing of a medical device is a complex process,which requires the contribution of a specialised multidisciplinary team. In the design process, efficacy and safety are the most important aspects [20,21]

The SuPort project [22] was founded by the United Kingdom government. It was a study which involved several professionals in an attempt to deal with CAUTIs issue.The multi disciplinary team was consisted of urologists, material scientist, hydrodynamic experts, ergonomics experts, surgeons, and nurses could find great alternative design solutions. In the beginning, the project portrayed how this team used a range of formal design methods in order to develop three medical devices. Devastatingly,the project ended before successfully producing a final device.

The newest group of reseachers that works for a company called Sharklet Technologies,Inc. are trying to come up with a new design for a urinary catheter, inspired from a structure of shark scales.This study have been focusing on the internal catheter surface. This new device would be made out of a non toxic coating surface to reduce the possibilities of cells or organisms adhesion on the surface without any chemical modifications or leeching of any substances from the raw material. This technology has been tested in marine applications where the bio-adhesion processes of complex organism such as as motile Ulva zoospores of common algae were studied [23,24]. The results could be seen as scientific proof that reproducing the anatomy of shark skin on a surface usually attacked by bacteria could reduce their adherence to it.

Chapter 3

Methodology

3.1 Introduction

In this project, several processes have been carried out and were included in the research methodology. The processes consist of the study is finding the dimensions and properties of fluid and catheters respectively , design the catheter tube using Design Modeler in ANSYS software, meshing and setting up the suitable boundary conditions for the simulations in ANSYS Fluent, running the simulation repeatedly for five more different configuration of catheter using the same diameter. After analysing the most promising configuration, the project is continued by using the configuration for five different diameters. The fluid solver used was ANSYS Fluent and the physical problem has been simplied by using the fluid properties of water, a fluid with similar physical properties to urine.

3.2 CFD approach

Computational modelling are enabling most of researches to be done in vivo and in vitro experiments, meaning computer-based simulations. Computational Fluid Dynamics are commonly known as numerical analyses of systems involving fluid flows. Many industrial processes involving fluid had been using this methodology since the sixties. Though the theoritical and experimental approaches are very significant in analysing the outcomes of a project, CFD gives few advantages such as time and cost reduction and the ability to perform studies that is difficult to perform experimentally.

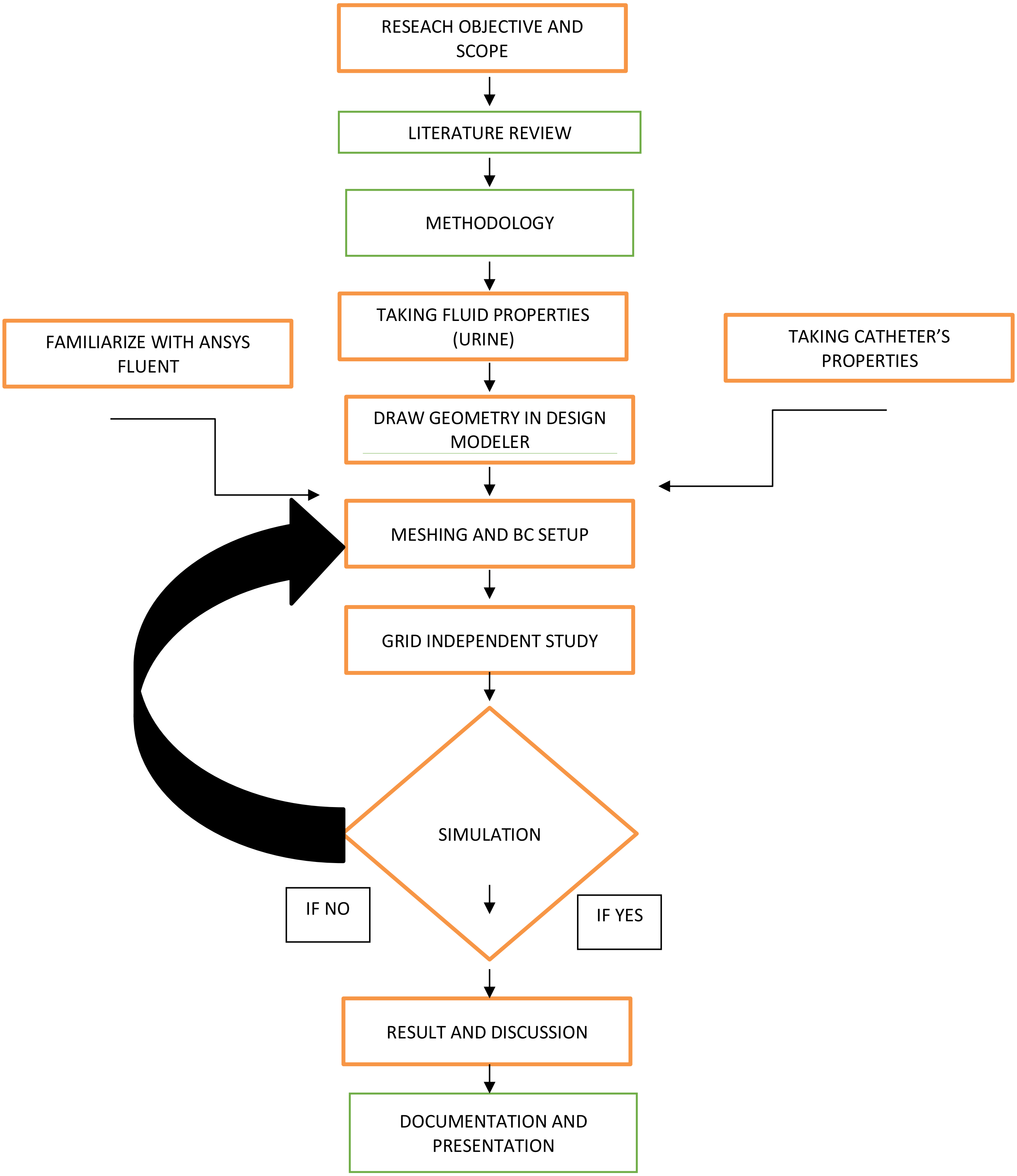


Figure 3.1 : Steps taken in methodology

For this project for CFD solution, ANSYS Fluent is used for fluid solver.

A CFD analysis consists of five main steps:

1. Computational domain (geometry) definition;
2. Meshing: the division of the domain in a number of points where the solution is calculated;
3. Fluid properties and boundary conditions definition;
4. Solution of the discretised representation of the model;
5. Post processing and validation of results.

In this study a finite volume method solver called ANSYS Fluent was used. Fluid characteristics, such as velocity, pressure and flow rate, are defined at nodes and both accuracy of solution and its calculation time are strictly related to the grid (mesh) quality and its fineness. ANSYS Fluent can be used to solve the equation of continuity (1) and the Navier-Stokes equation (2) for incompressible steady flow:

$$\nabla \cdot \boldsymbol{v} = 0, \qquad (1)$$

$$\boldsymbol{v}\nabla \cdot \boldsymbol{v} = -\frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2 \boldsymbol{v} + \boldsymbol{F}, \qquad (2)$$

where v, ρ, μ, and F represent the velocity, the pressure, the fluid density, the fluid viscosity and body forces, respectively. An experiment done by Melis,A et al at The University of Sheffield, in the view of reproducing experimental unpublished result, the fluid was modelled as water and the catheter geometry resembled the experimental setup. This showed of a reservoir mimicking the bladder, connected to a catheter. (Figure 3.2).

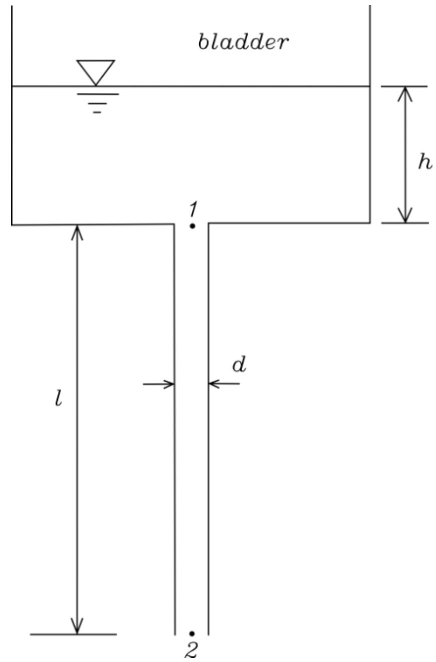


Figure 3.2 Model which mimics the experimental setup

A pressure was applied at the inlet, which coincides with point 1 in the scheme shown in Figure 7.

$$P_{\mathbf{1}} = P_a + \rho g h + \rho g l \qquad (3)$$

where ρgh was the head pressure due to the water inside the reservoir and P_a the atmospheric pressure. The last term ρgl considered the body forces in the model below the point 1. Atmospheric pressure was applied at the outlet which coincides with the point 2:

$$P_{\mathbf{2}} = P_a \qquad (4)$$

The non-slip condition (i.e. zero normal velocity at the wall) was imposed on the tube and catheter surfaces.

Simulations were carried out using a personal computer which is Toshiba Satellite M840-A759.. PC specification are shown in Table 1.

Table 3.1 - PC specifications

CPU	Intel Core i5 (2nd Gen) 3210M / 2.5 GHz
Number or core	Dual-Core
Total Memory	640GB HDD
Speed hard drive	5400 RPM
Cache/RAM	3MB / 4GB
Max Display Resolution (dpi)	1366 x 768
Operating System	Microsoft Windows 8 64-bit

3.3 Geometry

During the simulations, six different catheters sizes were used. The study was then divided into two different phases in which the configuration was changed. In the first phase, a 12CH/FR catheter tube was used in five different configurations which are a straight tube,a single loop tube, a double-loop tube, an L-shaped tube and an S-shaped tube. The second phase was performed using the most performed configuration to five different catheter tube diameters .The diameter used are 10,12,14,16,18 CH/FR.

Catheter

From the previous research, diameters and length of the tubes were available as shown in Table:

Table 3.2– Catheter used during the simulations and their proprieties[26]

Diamater	**Internal diameter [mm]**	**Length [mm]**
10	1.4	420
12	1.6	420
14	2.0	420
16	3.2	420
18	4.0	420

In this case, the experimental data provided the catheter and consequently both external diameter and length. Diameter units are usually given on French scale or French gauge, which are used to measure the size of a catheter. French size (Ch) is three times the external diameter in mm, i.e. a Ch18 catheter has an external diameter of 6 mm.

The catheter internal flow are closely related to the internal diameter and shape. However for this catheter, the internal cross-section does not have a standard shape but only in an asymmetrical semi-circle geometry (Figure). So for this project, it was decided to use a circular shape (Figure) with the same cross s.ection to the actual catheter. By using the catheter length and volume (obtained from previous reseach), the equivalent diameter was computed.

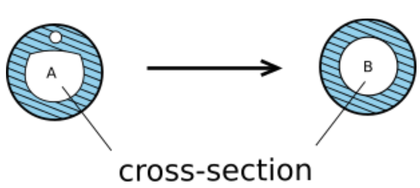


Figure 3.3 - Cross section of the catheter: (A) cross-section observed experimentally, (B) cross-section simplified for computational simulations as calculated from the external diameter.

Figures below show all the configurations chosen to simulate a CH 12 diameter of catheter tube.

1) Straight configuration

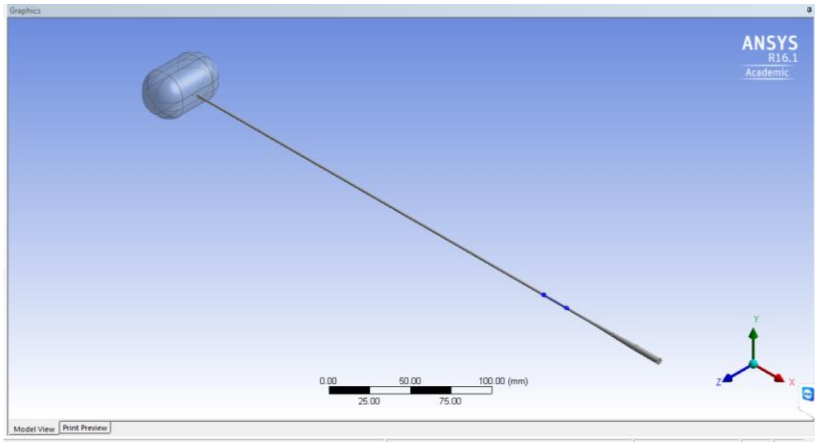


Figure 3.4: Catheter with straight configuration.

2) Loop configuration

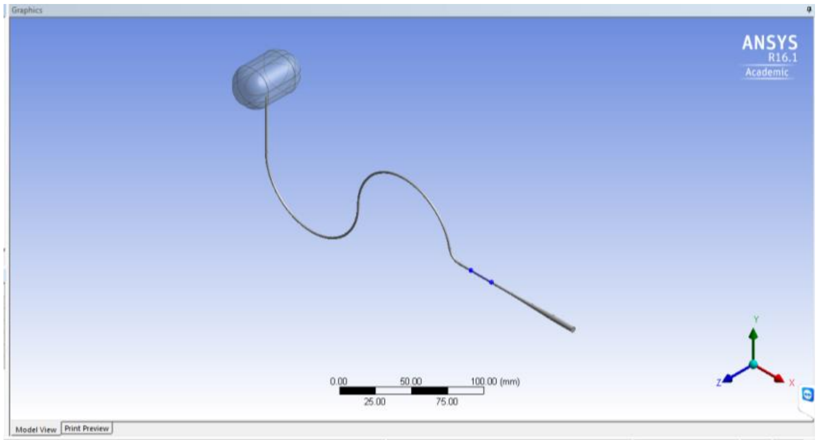


Figure 3.5: Catheter with loop configuration.

3) Double Loop configuration

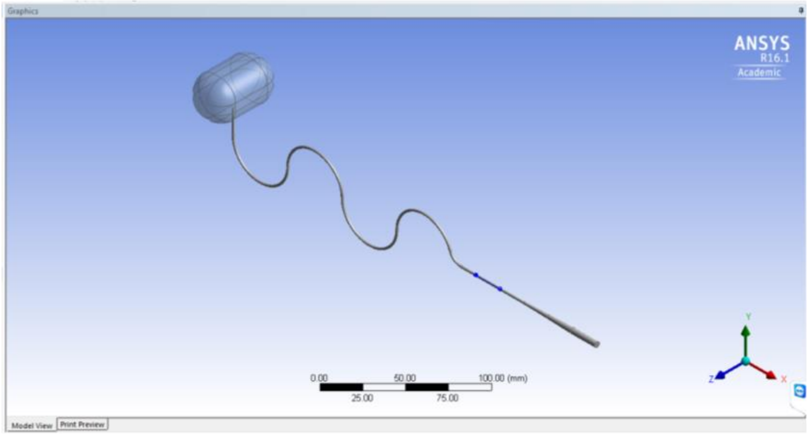


Figure 3.6: Catheter with Double Loop configuration.

4) L-shaped configuration

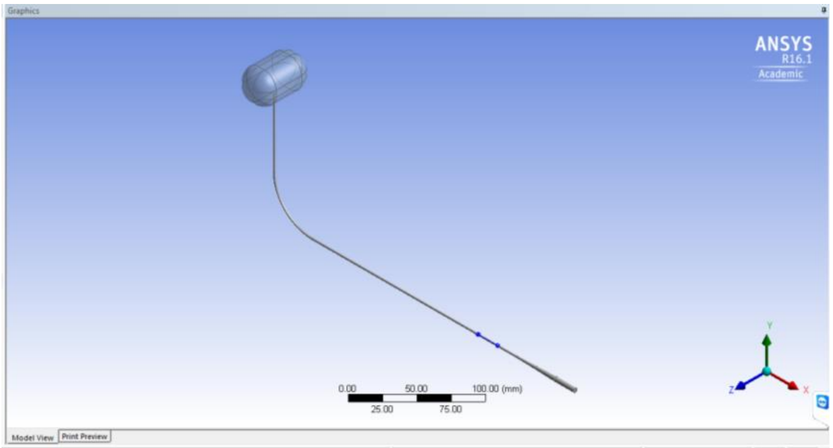


Figure 3.7: Catheter with L-shaped configuration

5) S-shaped configuration

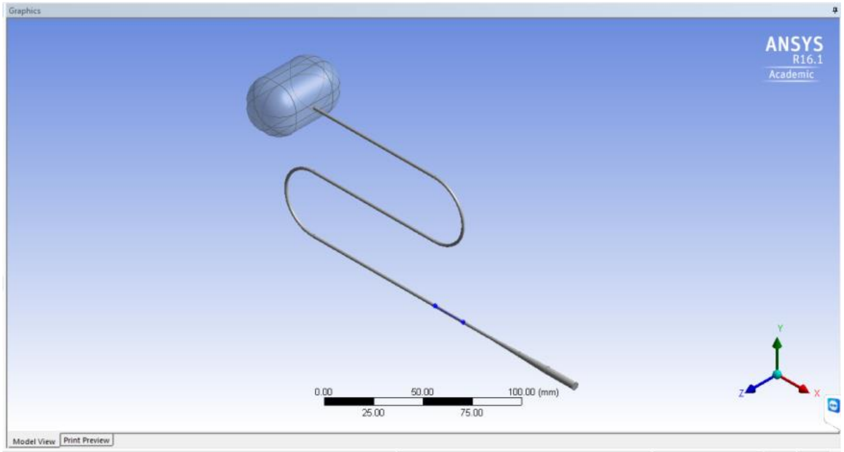


Figure 3.8: Catheter with S-shaped configuration.

3.3.1 Fluid properties

Before creating the mesh, it is important to define the flow properties of urine. Urine is considered as a non compressible and Newtonian fluid. A Newtonian laminar flow does not need a very refined mesh but able to reproduce the physics accurately. In the case of turbulent flow, the grid must be generated in accordance with the turbulence model used to perform the simulation.

The type of flow can be defined by the value of Reynold's number (Re). A laminar flow is when the internal flow have the value lower than 2300. If it is between 2300 and 400, then the flow is considered as transitional. Finally, if the Re is greater than 4000, the flow is turbulent []. The Re number is calculated using the characteristics length of the geometry used. This is a value usually known a priori, and in this study it is the internal diameter. This number includes also fluid properties such as the velocity (u), the kinematic viscosity (μ) and the density of the fluid used (ρ):

$$Re = \frac{\rho \cdot u \cdot D}{\mu} \qquad \rightarrow \qquad \begin{cases} Re < 2300 & Laminar \\ 2300 \leq Re \leq 4000 & Transition \\ Re > 4000 & Turbulent \end{cases}$$

The Re number was calculated for all the catheters used during the simulations. Since its value depends on the internal diameter and the flow velocity, the results obtained are different for each case and are reported in **Error! Reference source not found.**. The velocity was calculated based n the flow rate obtained experimentally.

Table 3 - Reynolds numbers related to the catheter used during the CFD simulations

Catheter internal diameter [mm]	$\boldsymbol{Re}$
Ch10	1998
Ch12	2325
Ch14	2718
Ch16	3012
Ch18	4493

The results show that the Re number is greater than 2300 in all cases, except for the catheter with CH10. This would imply the necessity to solve the CFD problem using a turbulence model. Depending on the fluid model employed, a different mesh with different properties was required.

The urine viscosity and density applied in the study were 0.654 mPa·s and 1,003 kg/m^3, respectively. Urine is similar to water in density and dynamic viscosity because it consists mostly of water. At a temperature of 37°C, the density and dynamic viscosity of urine are 1,003–1,035 kg/m^3 and 0.635–0.797 mPa·s, respectively. The viscosity changes according to temperature, although the change is negligible in the range of normal body temperatures from 35°C to 40.5°C.

3.4 Mesh

Since the properties of fluid is known, meshing can be done accurately. This is because the characteristics of turbulent flow are very different from laminar flows. The main differences are near the wall where strong gradients related to the dependet variable will add the computational cost of the analysis. Figure shows the velocity of these areas.

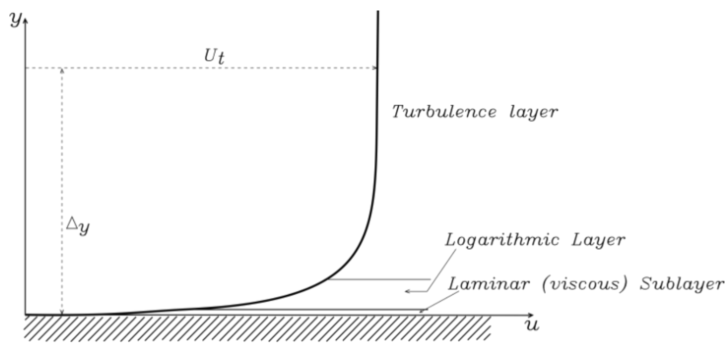


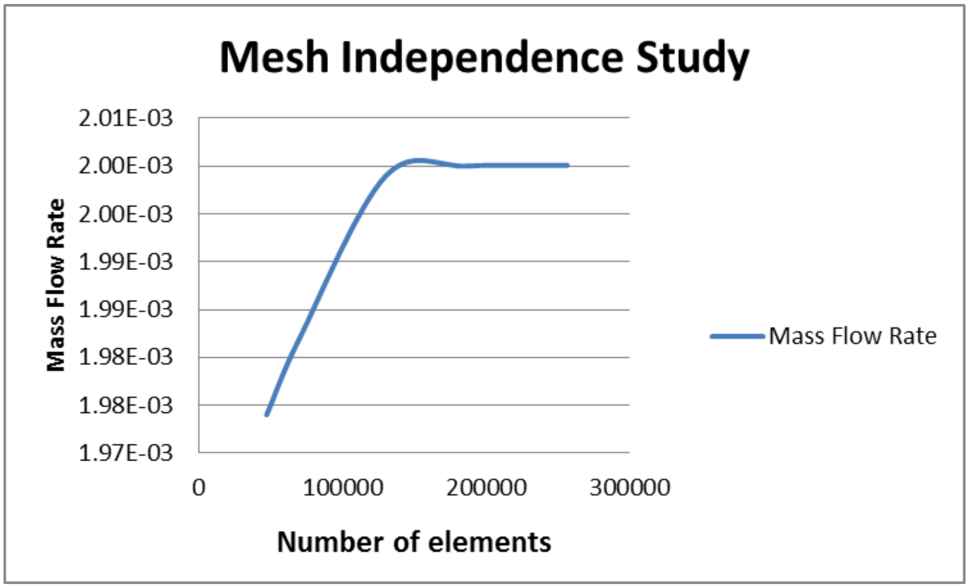
Figure 03.4 - Velocity profile near the wall in case of turbulent flow

Mesh independence study

Once the mesh was created, a convergence criteria independence study and mesh independence study were performed for each catheters, in order to choose the best possible mesh. The physical values monitored for each geometry where:

- Flow rate at the outlet (ml/s);
- Maximum velocity along the catheter (ml/s)
- Pressure (Pa).

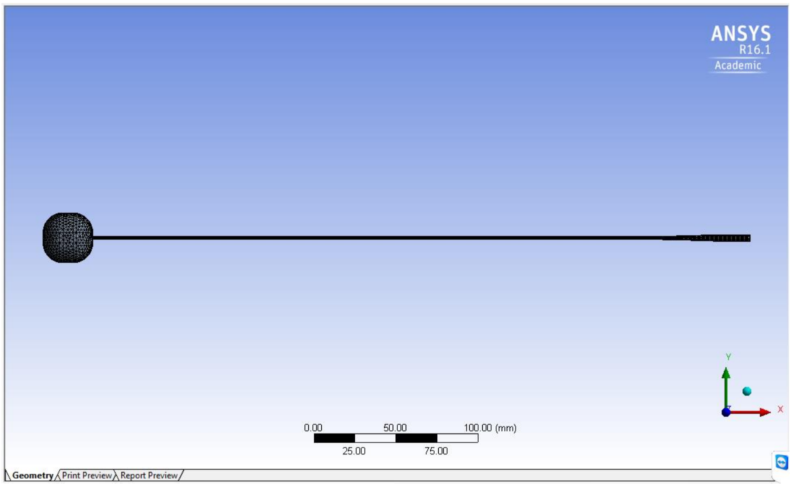
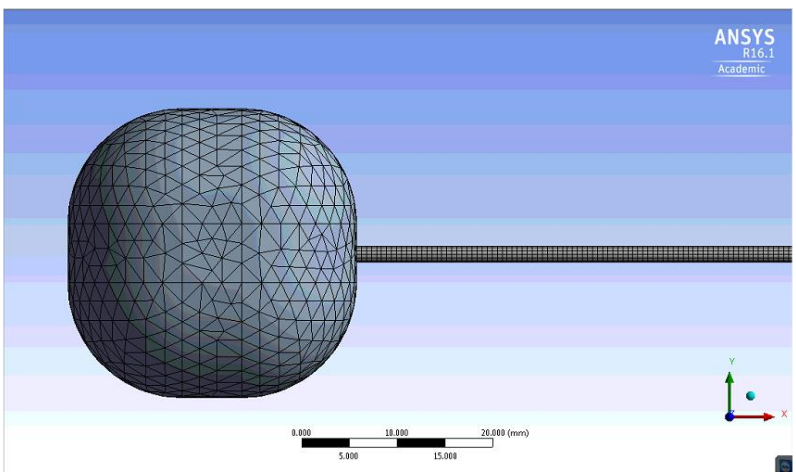
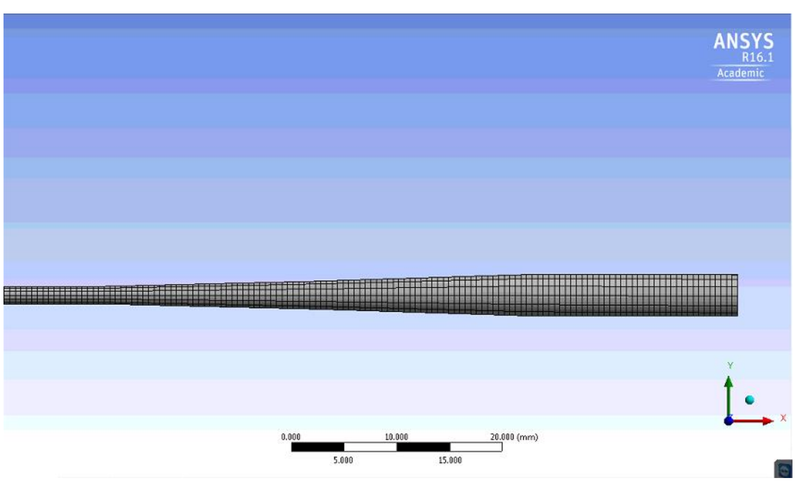
The study for one geometry started with the creation of 3 different meshes with different properties in terms of maximum elements and number of layers. The mesh independence study was then performed using those values calculated for each mesh. To do that the same procedure used for the convergence criteria independence study was used. An example of result is shown in Graph 1.

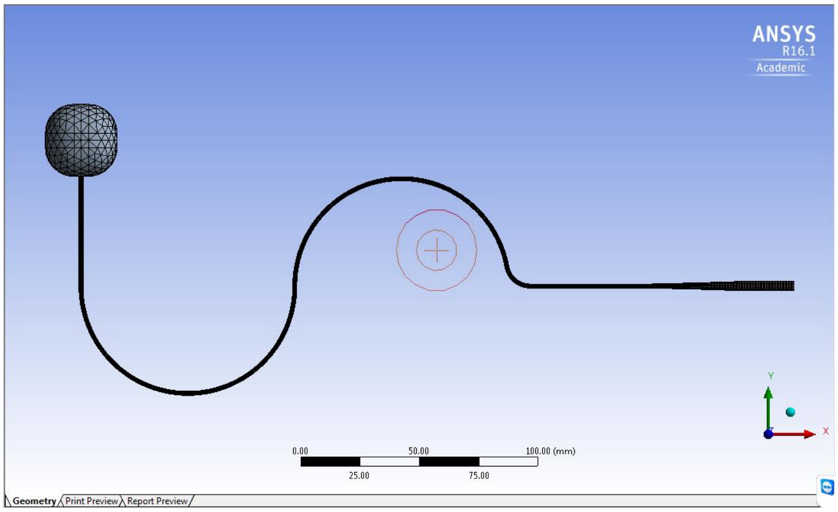


Graph 1: Physical values of maximum outlet pressure against the number of mesh elements for one case of study during the simulations.

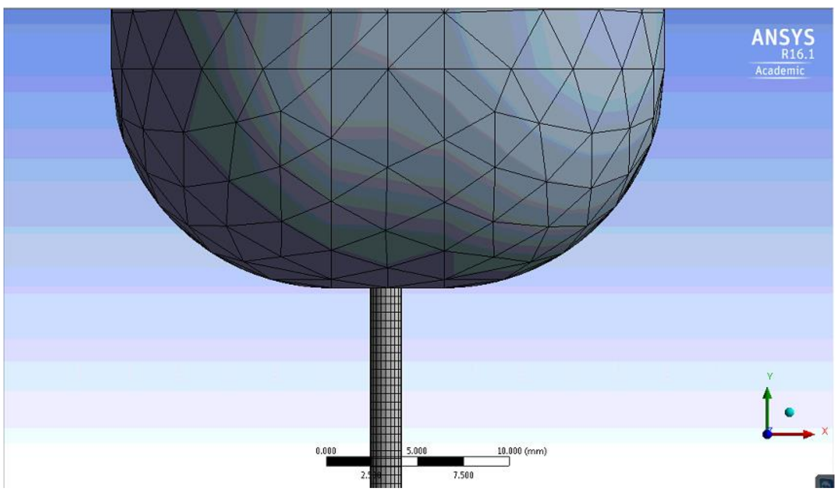
First phase of the simulation is by meshing the five different configurations.Subsequently meshing for five different diameter on the most desired configuration.

Table 3. 4 : All the meshing for five configurations and five diameters of catheter.

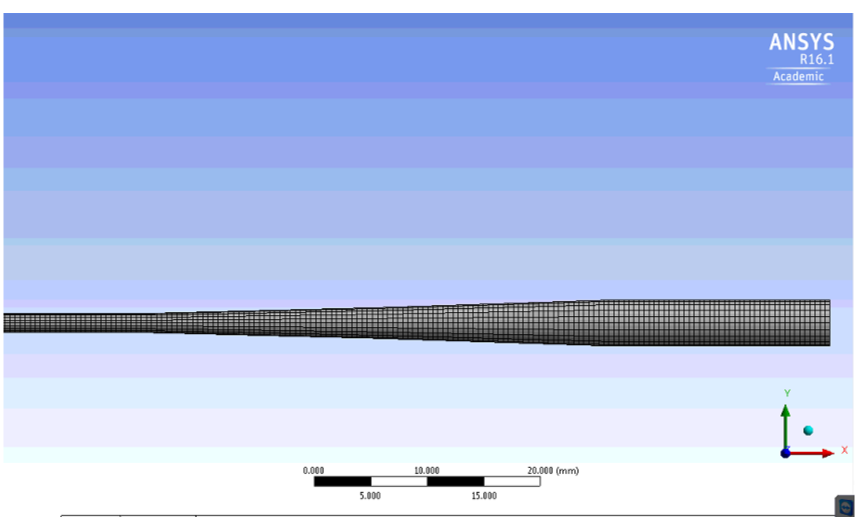
Meshing	Description of meshing
	Whole
	Bladder and inlet
	Outlet Nodes: 30027
(a) Straight	Elements: 47428



Whole



Bladder and inlet

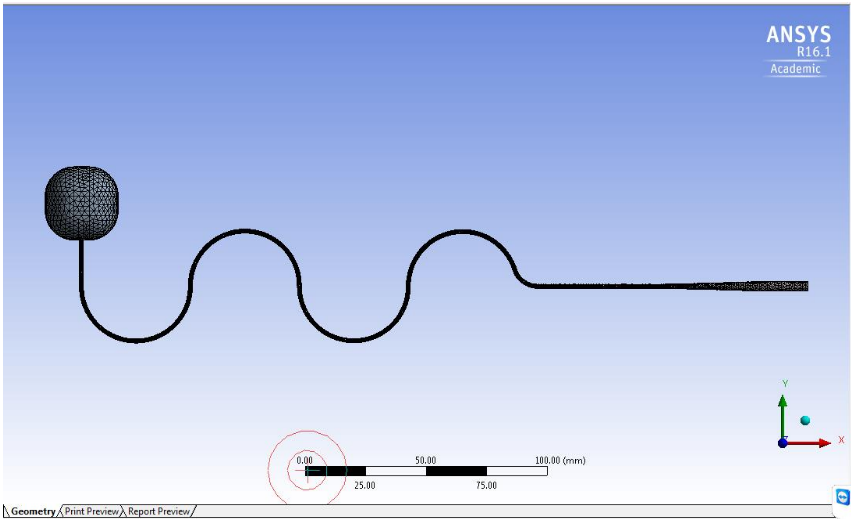


Outlet

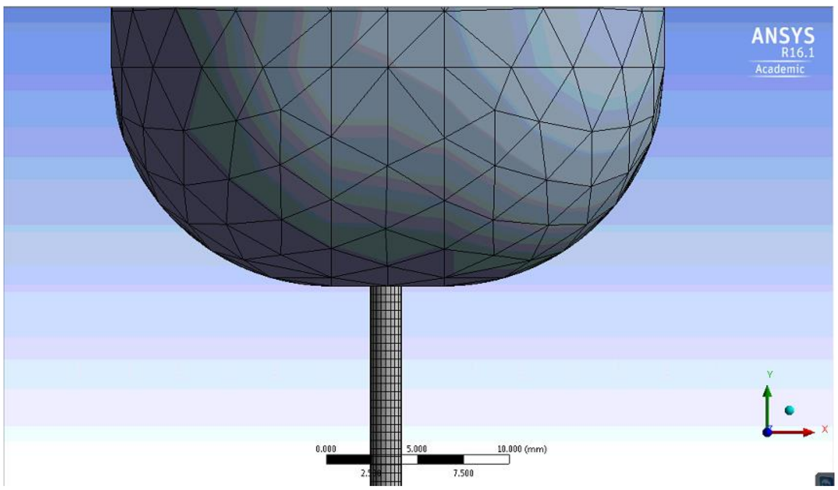
(b) Loop

Nodes: 54988

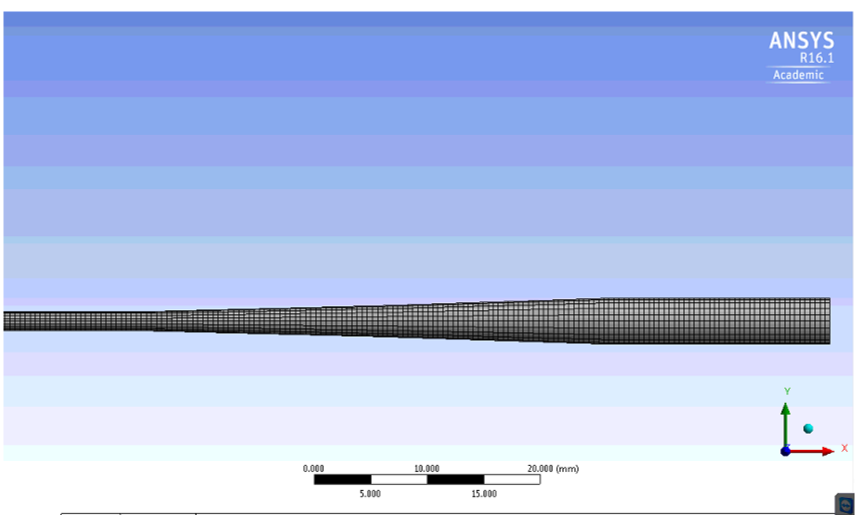
Elements: 59658



Whole



Bladder and inlet



Outlet

(c) Double Loop

Nodes: 80407

Elements: 364618