Atlantic International University
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2/12/2024

Fluid Mechanics

Course Title	Fluid Mechanics
Course Code	FME426
Name	Santanu Mishra
Student ID	UM84034CH93252
Degree	MS in Chemical Engineering

Signatures	
Prepared By:	Santanu Mishra **Santanu Mishra** Student, AIU
Reviewed By:	**Mr. Tobi Rotimi Opoola** Tutor, AIU
Approved By:	**Dr. Edward Lambert** Advisor, AIU

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1. Chapter 1: General Introduction:

1.1 Contextual Data

Fluid mechanics is the study of fluids at rest (fluid statics) and in motion (fluid dynamics). Fluid statics examines fluids subjected to forces but not moving, analyzing properties like pressure, buoyancy, and stability. Fluid dynamics studies the kinematics and kinetics of fluid flows, using equations like continuity and Navier-Stokes to analyze concepts like vorticity, turbulence, and boundary layers. Fluid Mechanics is a branch of Physics which commands upon study the dynamics and forces acting on it. Its uses in engineering are numerous, including hydraulic, Aeronautical and Chemical Engineering. The fundamentals of this research topic to the fluid dynamics is on due aiding mechanics which focuses so much at specific behaviour fluids in motion. Understanding fluid mechanics is very important in developing and checking systems that involve fluids, for instance tanks or pipes with liquid flowing through them such as turbines.

This study seeks to offer the underlying core ideals in fluid mechanics. To begin this study fluid dynamics and its properties will be defined to establish the topic under discussion from where a further analysis of static fluids would follow with an elaborate coverage about pressure, buoyancy as well floatation. Fluid kinematics and dynamics will be investigated further from an aspect of flow features, continuity alongside governing equations that govern fluid motion shall be profiled. Dimensional analysis and model studies as methods of developing fluid systems will also be covered by the course.

Taking the extensive scope, the dissertation will be dedicated to tube flow dynamics study and discuss a great number of factors influencing fluid rate and frictional loss. The primary focus of the study will be boundary layers, especially their formation on surfaces and associated drag forces. The main aim of this dissertation is given to deliver a theory and practical knowledge about fluid behaviour in different conditions. The gained knowledge will be applicable to the smooth functioning of many fluid handling structures within a broad range of technical sections.

1.2 Background Information

The field of fluid mechanics has evolved over many centuries, with early intellectuals like Archimedes establishing the fundamental principles of hydrostatics. Bernoulli's principle, developed during the 18th century, establishes a relationship between pressure, fluid velocity, and elevation. The Navier-Stokes equations, fundamental to the study of fluid dynamics, were formulated during the early 19th century. During the 20th century, aerodynamics saw significant advancements due to the emergence of aviation, which required a sophisticated comprehension of fluid dynamics. Revolutionary experimental research has enhanced fluid theories, such as the studies undertaken at British research institutions using wind tunnels.

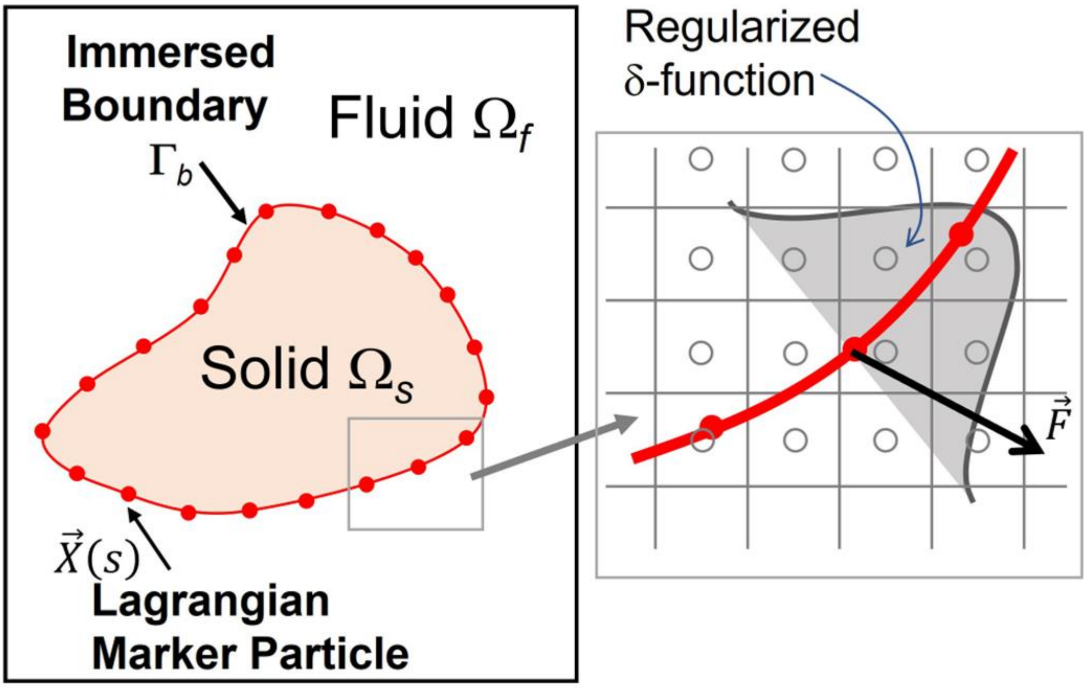


Figure 1: Schematic of a viscous incompressible flow inside a rectangular two-dimensional domain

(Source: Mittal & Seo, 2023)

Fluid mechanics is crucial in several technologies nowadays. Boundary layers, along with turbulence, substantially influence the design of aeroplanes (Brunton *et al.* 2020). Proficiency in pipe flow facilitates the advancement of oil pipelines and wastewater systems. Multiphase flow physics facilitates the optimization of processes in chemical plants. Analysis of compressible flow assists in the design of jet engines and gas turbines. Computational fluid dynamics uses simulation techniques to analyse intricate fluid dynamics. Fluid mechanics also applies to developing areas such as microfluidics, renewable ocean energy, and space exploration.

This dissertation aims to integrate well-established and current information in fluid mechanics. The analysis will rely on fundamental experiments and equations established by trailblazers. Theoretical underpinnings will be connected to realistic engineering applications, showcasing their tangible significance in real-world scenarios. It will demonstrate fluid mechanics as a dynamic and varied discipline essential to technological progress.

2. Chapter 2: <u>Definition of the Investigation (or Issue)</u>:

2.1 Statement of the Issue

Fluid mechanics comprises a wide array of phenomena and fundamental concepts that control the behaviour of fluids. Nevertheless, it is difficult to thoroughly address the whole range of fluid mechanics topics within one dissertation's limitations. Therefore, it is crucial to use caution when determining the precise problems and subjects that need to be tackled. The primary objective of this inquiry is to establish a solid understanding of the fundamental principles of fluid mechanics (Garnier *et al.* 2021). The primary objectives are to develop comprehension of fluid characteristics, equilibrium, motion, dynamics, dimensional analysis, flow in pipes, and boundary layers.

Furthermore, there will be a strong emphasis on applying these principles to engineering systems and situations. Although advanced aspects of fluid mechanics will not be covered, the chosen subjects will provide the reader with essential information and problem-solving abilities that may be used across the discipline. The dissertation will catalyse further focused exploration in fluid mechanics fields such as aerodynamics, hydraulics, or computational approaches. Clearly defining and establishing the scope of the research is crucial for attaining thoroughness in the selected areas of attention.

2.2 Description of the Issue

Fluid mechanics is a comprehensive discipline that studies the characteristics and actions of both liquids and gases. Fluid mechanics involves complex and multi-dimensional challenges vital to many engineering systems. Liquids and gases have a number of physical characteristics peculiar to them that are not the same as those of solid bodies. The study is inclusive of highly complex physics principles and advanced mathematical tools which include differential equations, computer approaches among others (Raissi *et al*. 2020). Special problems are associated with the modelling of multiphase flows, turbulence and elasticity. In the situation when one needs to transfer complicated aspects of fluid mechanics in a brief and understandable form both for students or during practical applications, this may be difficult. This inquiry is set to provide a comprehensive and understandable overview of the basic principles that govern fluid mechanics. Detailed explanation of the fundamental equations, concepts and applications will allow for understanding as well as improved memory retention. Utilising examples to clarify concepts will increase their utility in practical systems. The emphasis of the description will be on physical fundamental processes rather than mathematical derivations in relation to fluid phenomena. To ensure uniform understanding. It is crucial to tackle the difficulties in elucidating fluid mechanics principles to conduct a successful inquiry.

3. Chapter 3: Dynamics of the Anticipated Solution:

3.1 Goal(s) and Objective(s) of the Investigation

Goal(s)

The goal of this investigation is to provide a comprehensive grounding in fluid mechanics principles that equips the reader with a functional understanding of fluid behaviour and dynamics. Possessing core knowledge will enable application of fluid mechanics concepts in engineering design and analysis across diverse technological contexts.

Objective(s)

- Explain fundamental fluid properties and the distinctions from solids
- Derive and apply key equations describing fluid static pressure, buoyancy, and stability
- Analyse fluid kinematics including flow patterns, continuity, and modelling methods
- Elucidate governing equations of fluid motion and dynamics principles
- Demonstrate the use of dimensional analysis and scaled models in fluid systems
- Describe laminar/turbulent flows and boundary layers on surfaces and in pipes
- Relate theory to practise through examples of fluid mechanics engineering applications

3.2 Methodology

This dissertation will use secondary sources to examine the fundamental principles and practical uses of fluid mechanics. A comprehensive literature study will be undertaken to collect insights from influential theoretical articles, experimental research, and practical engineering publications. Query to databases will be made in order to identify relevant academic publications.

The focus of the search will be on important issues such as fluid dynamics, fluid features, dimensional analysis, pipe flow, boundary layer theory, aerodynamics, and computational fluid dynamics. The data will be restricted to papers from journals (Rabault *et al.* 2020). This literature study shall try to extract fundamental equations, theoretical frameworks, experimental techniques, and real-life applications related to each area of interest. Subjective descriptions and objective numerical data will be gathered. Considerable emphasis will be placed on impactful publications including Reynolds' studies on pipe flow and Prandtl's papers on boundary layers since they have played a crucial role in shaping modern fluid mechanics. The study will also touch upon recent developments such as the direct numerical modelling of turbulence. Through secondary research, the dissertation will accumulate the core knowledge and background of fluid mechanics.

4. Chapter 4: Overall Outcomes:

4.1 Strategy and Techniques

The dissertation will use established pedagogical techniques to proficiently communicate principles and practical applications of fluid mechanics. The information will be organised in a logical manner, progressing from fundamental concepts to intricate dynamics. The use of clear and concise language, uniform terminology, and mathematical symbols will enhance understanding.

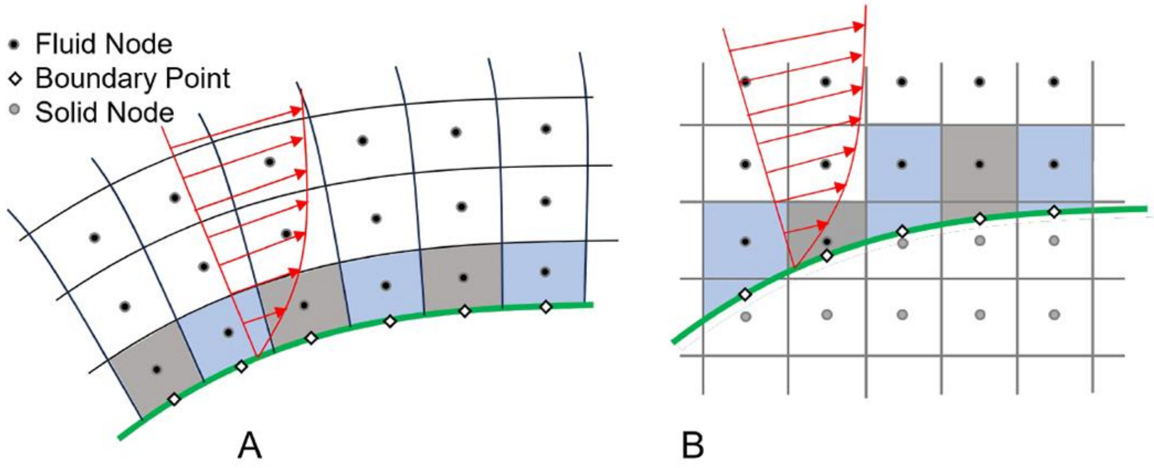


Figure 2: Schematic of a (A) curvilinear body-fitted grid and (B) Cartesian grid and cut-cells around a curved boundary

(Source: Mittal & Seo, 2023)

The properties of fluids will be detailed first, contrasting them with solids. Clear definitions and examples will illustrate density (ρ), viscosity (μ), compressibility (β), surface tension (σ), and vapour pressure (Papanastasiou *et al.* 2021). To explain fluid statics, pressure measurement devices like manometers, buoyancy physics ($Fg = \rho gV$), and stability principles like centre of pressure will be clarified. Hydrostatic equation fundamentals ($dp/dz = -\rho g$) will be derived. Kinematics will relate flow types (laminar, turbulent), visualisation methods (streamlines, pathlines), and governing continuity ($\nabla \cdot V=0$) and potential equations ($\nabla 2\varphi = 0$).

Dynamics will unpack the Navier-Stokes equations, exploring Euler ($\rho Dv/Dt = -\nabla p$), Bernoulli ($P + 1/2\rho v2 + \rho gh = \text{constant}$), and momentum ($F = m(dv/dt)$) equations applied in venturis, orifices, and pitot tubes. Dimensional analysis techniques will be elucidated via Buckingham Pi Theorem and similitude. Pipe flow will integrate theory, examining laminar flow ($Q = (\pi R4\Delta P)/(8\mu L)$), turbulence, friction factors (f), head loss (hl), and flow distribution.

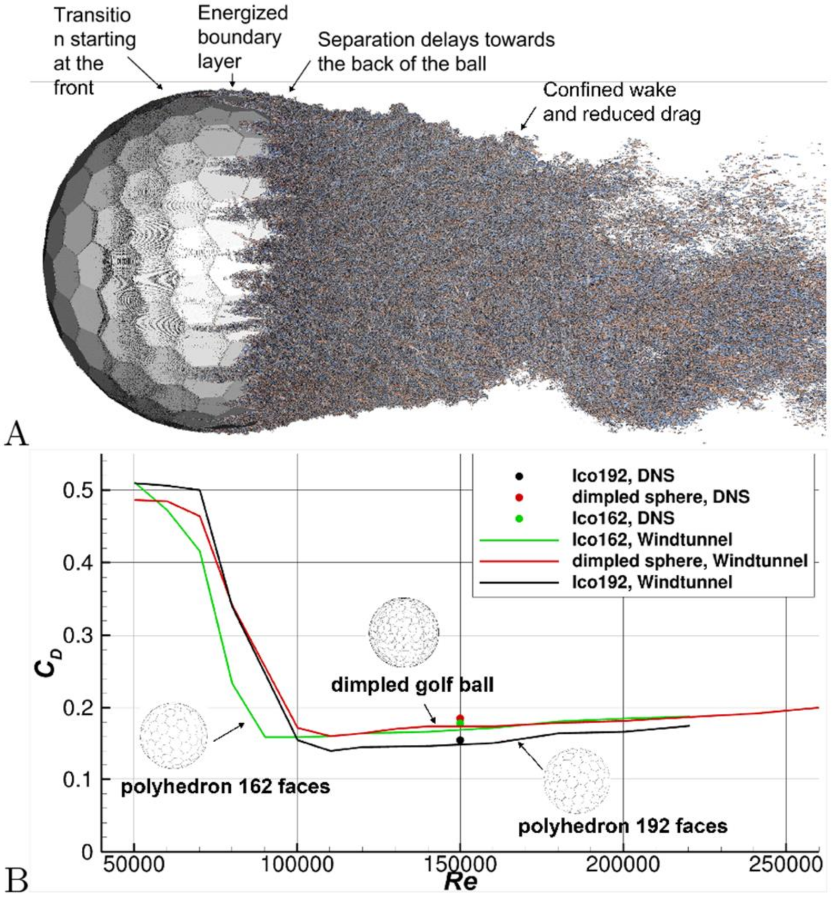


Figure 3: A: Isosurface of the Q-criterion visualising vortical structures near the top of the tessellated sphere at Re=1.1 × 105. B: Drag coefficient versus Re for three different golf balls, with dimples, tessellated with 162 polyhedron faces, and 192 faces. Wind tunnel measurements are shown with solid lines and DNS values are shown with dots.

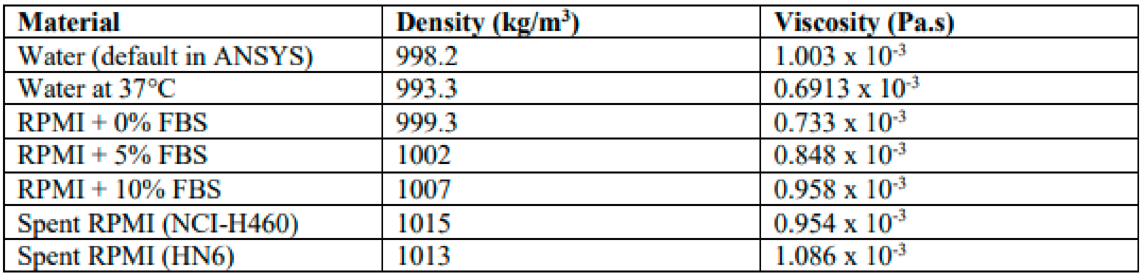
(Source: Mittal & Seo, 2023)

The study of the boundary layer will include the consideration of displacement thickness (δ), momentum thickness (θ), and energy thickness (δ), as well as separation parameters. Throughout the course, ideas will be strengthened via the use of charts, graphs, and drawings that portray the movement of fluids. Engaging in practice tasks facilitates self-assessment. Real-life illustrations will provide a link between theoretical concepts and practical applications in many engineering sectors. In summary, successful approaches will cultivate fundamental skills in the application of fluid mechanics concepts.

4.2 Results

4.2.1 Fluid Properties and Fluid Statics

This section introduces fundamental concepts related to fluid characteristics, such as density (ρ), viscosity (μ), surface tension (σ), compressibility (β), and vapour pressure (Pv). The study examined fundamental differences between solid and fluid behaviour, specifically focusing on the fluid's capacity to flow and undergo continuous deformation when subjected to shear stress. The significance of comprehending fluid characteristics in areas such as hydraulics, aerodynamics, and chemical processing was shown in many instances.



Material	Density (kg/m^3)	Viscosity (Pa.s)
Water (default in ANSYS)	998.2	1.003×10^{-3}
Water at 37°C	993.3	0.6913×10^{-3}
RPMI + 0% FBS	999.3	0.733×10^{-3}
RPMI + 5% FBS	1002	0.848×10^{-3}
RPMI + 10% FBS	1007	0.958×10^{-3}
Spent RPMI (NCI-H460)	1015	0.954×10^{-3}
Spent RPMI (HN6)	1013	1.086×10^{-3}

Figure 4: Properties of water and different culture media formulations assigned.

(Source: Poon, 2022)

The governing equations of fluid statics were constructed and used, including the hydrostatic pressure equation ($p=\rho gh$), which states that pressure changes linearly with fluid depth. The analysis of manometers as pressure-measuring devices focused on measuring liquid column height, considering the varying density between the columns (Kavokine *et al.* 2021). The concept of buoyancy in physics was explained using Archimedes' principle ($F_b = \rho gV$), which establishes a relationship between the weight of the displaced fluid and the buoyant force. The study of stability theory investigates the effects of the centre of pressure and metacentric height. The equation of Bernoulli, expressed as $P + 1/2\rho v2 + \rho gh = \text{constant}$, was deduced to establish a relationship between pressure, velocity, and height within the context of an energy balance along streamlines.

4.2.2 Fluid Kinematics and Dynamics

The analysis of fluid motion started with the study of kinematics. The categorization of flows into laminar and turbulent states was established based on the dimensionless Reynolds number ($Re = \rho VL/\mu$). Streamlines were established as flow visualisation techniques to represent velocity patterns (Fields & Yen, 2021). The continuity equation ($\nabla \cdot V=0$) was created to represent the principle of mass conservation in fluid dynamics mathematically. Potential flow methods simulate flows by solving the Laplace equation ($\nabla 2\varphi = 0$), assuming that viscous effects may be ignored.

$$\begin{aligned} &\nabla \cdot \vec{v} = 0 && \text{incompressibility on } \Omega \\ &\rho\dot{\vec{v}} = \rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\,\vec{v}\right) = -\nabla p + \mu\Delta\vec{v} + \vec{f} && \text{conservation of momentum on } \Omega \end{aligned}$$

Figure 5: Incompressible Navier-Stokes Equations

(Source: Wandel et al.,2020)

The analysis of fluid dynamics included the examination of the Navier-Stokes equations. However, specific variants of these equations, such as the Euler equations ($\rho Dv/Dt = -\nabla p$), were explicitly studied for irrotational and inviscid flows. Bernoulli's equation applies to venturi metres, orifices, and other devices, establishing a connection between pressure and velocity. The momentum principles, expressed as $F = m(dv/dt)$, describe the flow behaviour that changes direction.

Dimensional analysis was introduced to obtain dimensionless parameters to describe situations. Using techniques such as Vaschy-Buckingham Pi (Π) has revealed crucial characteristics and facilitated the examination of similarity. The development of dynamic similitude standards allowed for the building of scaled models for testing, which included matching Reynolds, Froude, and other dimensionless values. An analysis was conducted on the limitations of distorted models concerning the relaxation of similitude.

4.2.3 Flow Through Pipes

The analysis focused on the many parameters that influence the flow rate and pressure loss in pipe flow, providing comprehensive coverage. The Hagen-Poiseuille equation (Q = (πR4ΔP)/(8μL)) was used to simulate laminar flow, taking into account the variables of radius, pressure drop, and length. The characterization of turbulence included the use of the Moody diagram, which establishes a relationship between friction factors (f), Reynolds number, surface roughness, and other relevant characteristics (Alves *et al.* 2021). The Darcy-Weisbach equation utilises friction elements to compute the decrease in pressure. The energy equations create a correlation between the force needed to overcome friction, the kinetic energy, and the pressure energies across distinct sections of a pipe. The equations for head loss were constructed using Bernoulli's principle in order to represent both significant and small losses. The analysis focused on complex pipe networks that consisted of several parallel or series branches.

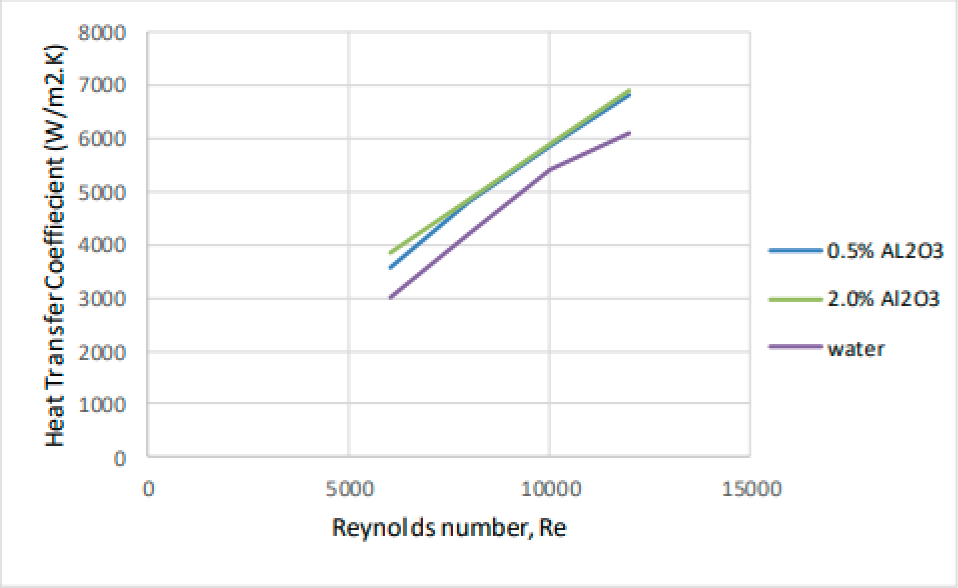


Figure 6: Effect of nanoparticle concentration on convective heat transfer coefficient

(Source: Elfaghi *et al.* 2022)

Boundary layer analysis forms a scientific study that focuses on the growth and nature of fluid layers over surfaces as established by Prandtl. To resolve laminar boundary layers and determine velocity profiles, the Blasius solution was adopted. The equation for momentum integral uses displacement thickness (δ*), momentum thickness (θ), and energy thickness (δ**) to describe the growth of the boundary layer. A study of the transition to turbulence was simulated, where particular attention was paid to analysing features like the form factor with regard to the risk of separation. The methods of control of the boundary layer were analysed to minimise drag and to prevent separation.

5. Chapter 5: Analysis:

5.1 Interpretation of Results

The results imply a profound grasp of basic fluid mechanics principles like static, kinematic, dynamic, and applied aspects. It is evident that the primary attributes of fluids namely viscosity and compressibility play a key role in describing their complex rheological behaviours and their important contribution to fluid flows (Lohse, 2022). The essential correlations between pressure, velocity and height are supplied by the fluid statics equations, such as Archimedes' principle and Bernoulli equation.

The link between the theoretical aspects and application of the practical issues is an attractive component of the study of kinematics and dynamics. The foundation for investigating fluid motion relies on the Navier-Stokes equations. Alternatively, approximations like the Euler equations lead to more convenient analysis, especially in aerodynamics. Dimensional analysis is important for the construction of scaled models with Buckingham Pi similarity assessment to evaluate engineering systems.

The dynamics of interior pipe flows can be applied to information. There is a link between the pressure losses and features such as flow rate, radius, roughness among others that are regulated by the equations governing the flow of fluids in pipes (Peng *et al.* 2020). This provides critical knowledge for technical applications like pipeline design and pumping systems.

The holistic study of the boundary layer and concepts that are based on notions that incorporate displacement thickness provide insights into ubiquitous fluid dynamic phenomena. Momentum integral methods can be used to model the development of turbulent and laminar boundary layers and the separation characteristics that underlie them (Cai et al. 2021). This information is widely used in many settings from airfoil construction to chamber combustion.

The balanced theoretical background and practical examples allow the reader to successfully apply the concepts of fluid mechanics to many cases, for example, to hydraulic systems, chemical processing plants, and aerospace. Acquiring basic knowledge and analytical abilities is a basis for pursuing further study and research in many subfields of fluid dynamics.

5.2 Questions about alternatives

While the dissertation offers an extensive investigation of core fluid mechanics topics, further questions emerge on additional areas that could be explored to supplement the analysis:

- How could computational fluid dynamics methods be incorporated to demonstrate numerical modelling approaches alongside theoretical and experimental concepts? Modern CFD techniques like direct numerical simulation provide new tools for investigating flows.
- What additions could expand the practical component? More examples solved through software packages or customised code could better link theory to practise. Design problems could strengthen proficiency.
- How might the dissertation be adapted to focus on a particular fluid mechanics subfield like aerodynamics, hydraulic systems, or microfluidics? Tailoring the emphasis could increase specificity for different engineering domains.
- What opportunities exist to go more in-depth on mechanics fundamentals like dynamic similitude for scaled models or specific approximated forms of the Navier-Stokes equations? Strengthening the theoretical foundations could improve conceptual grasp.
- How could the scope be expanded to include multiphase flows, non-Newtonian fluid behaviour, compressible flow, or other advanced areas? Introducing additional topics would broaden the coverage.

Exploring these options may improve the inquiry in certain areas, but it is important to avoid weakening the main topic or going beyond what is achievable in a single dissertation.

Nevertheless, the issues emphasise possible avenues to enhance the understanding of fluid mechanics.

6. Chapter 6: Conclusion:

The dissertation has thoroughly examined fundamental ideas and principles in fluid mechanics. The subject matter started with the characteristics of fluids and their equilibrium, then advanced to include the study of fluid motion, including its kinematics, dynamics, dimensional analysis, internal flow inside pipes, and the behaviour of fluid layers near boundaries. The fundamental fluid behaviour control equations were developed and elucidated, including Archimedes' principle, the Navier-Stokes equations, and the Hagen-Poiseuille equation. Both the theoretical underpinnings and actual technical implementations were given equal importance.

The studies provide readers with essential information and analytical abilities to apply concepts of fluid mechanics in many circumstances. The dissertation serves as a fundamental basis and catalyst for further exploration into specialised areas within fluid dynamics. Although further enrichment might enhance certain subjects, the primary emphasis ensures a strong foundation. This dissertation has effectively accomplished its objectives of imparting basic information in fluid mechanics, elucidating the basic principles of physics, deriving mathematical equations, and establishing a link between theory and practice in the real world-based systems. Readers are provided with the opportunity to analyse fluid systems and to acquire the necessary skills for engineering applications.

6.1 Recommendations

Based on the dissertation analysis and conclusions, the following recommendations can be made to further build upon this work:

- Broaden the scope of computational fluid dynamics methods to showcase numerical simulation techniques as a way to analyse flows. This would go with the theoretical and empirical notions.
- Include more detailed case studies solved by software packages or customised code to connect theory with practice. Design issues could also increase skill.
- Develop the focus to target a particular sub-area such as aerodynamics, hydraulic systems, microfluidics (Awad *et al*. 2020). This would increase specificity for different engineering domains.
- Give a more thorough analysis of basics such as dynamic similarity for scaled models and approximate Navier-Stokes equation forms. Strengthening theoretical foundations would be desirable.
- Incorporate further advanced subjects for instance multiphase flow, non-Newtonian fluids, compressible flow, and others among others to diversify. This would open up exposure to a broader spectrum of fluid mechanics areas.
- Include more practical calculations to show the practical implementation of key equations. This would help understanding and problem-solving ability.

Include more practical examples that are drawn from different engineering disciplines to show in how many different real-life situations fluid mechanics is applied. More examples from the real world would highlight relevance.

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