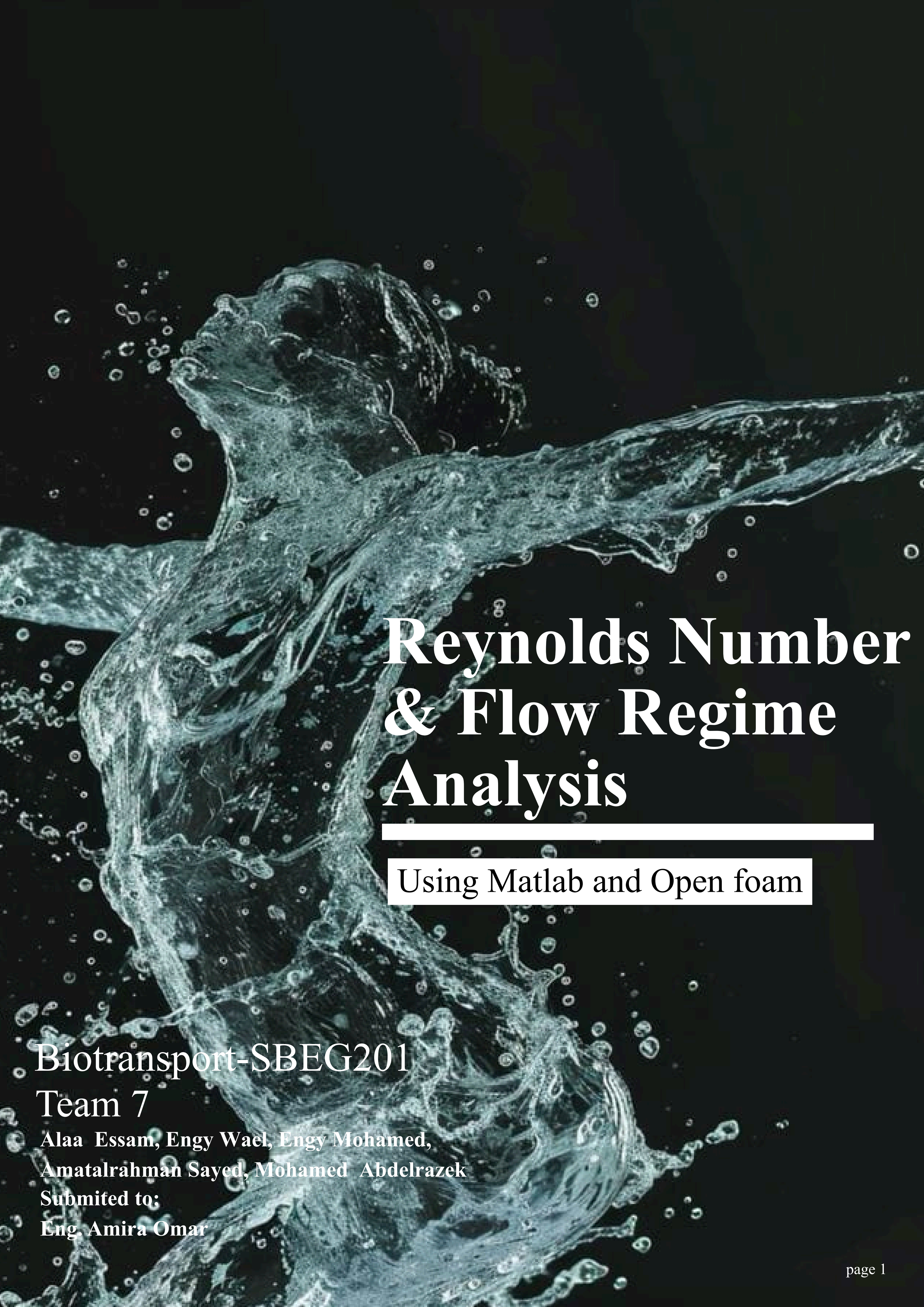

Reynolds Number & Flow Regime Analysis

Using Matlab and Open foam

Biotransport-SBEG201

Team 7

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1. Introduction

One of the most basic dimensionless parameters in fluid mechanics is the Reynolds number (Re). It describes the proportion of viscous to inertial forces in a fluid flow and is essential in identifying the type of flow regime, such as turbulent, transitional, or laminar.

Fluid particles travel in parallel, smooth layers with little mixing in laminar flow ($Re < 2000$). An unstable state where disturbances start to increase is represented by transitional flow ($2000 \leq Re < 4000$). Chaotic fluctuations predominate in turbulent flow ($Re \geq 4000$), which improves mixing and momentum transfer.

Because it affects blood flow dynamics, airflow in respiratory tracts, and transport in artificial organs and medical devices, an understanding of the Reynolds number is crucial in biomedical and engineering systems. The purpose of this project is to use MATLAB computational modeling to analyze and visualize how the Reynolds number affects flow regimes, velocity profiles, and friction factors.

2.Objectives

This assignment's primary goals are:

1. determine Reynolds numbers for different pipe diameters, velocities, and fluids.
2. use the calculated Reynolds numbers to categorize flow regimes.
3. see laminar and turbulent flow velocity profiles.
4. examine how the Reynolds number affects the Darcy friction factor.
5. develop an interactive Reynolds number calculator.
6. use streamlines to conceptually model and depict flow regimes.

3. Methodology

The analysis was executed using MATLAB R2025b as the primary computational tool to generate, process, and visualize all theoretical flow data. The approach was structured into four main steps: data definition, analytical calculation, comparative visualization, and advanced simulation.

1. Data Sources and Analytical Framework

The fluid property database was constructed to ensure maximum contrast, including standard engineering fluids (Water, Air) and critical biofluids (Blood, CSF). Density (ρ) and Dynamic Viscosity (μ) values were sourced from standard biotransport and engineering reference tables. The core of the analysis relies on established fluid mechanics principles:

I. Reynolds Number and Classification (Part 1)
The flow regime was classified using the fundamental definition of the Reynolds Number (Re), which balances inertial and viscous forces: $\mathbf{Re = (\rho\, V\, D) / \mu}$

II. Theoretical Velocity Profiles (Part 2)
Velocity profiles were generated based on established theoretical models for comparative visualization:
Laminar Flow: Assumed to be fully developed, governed by the Parabolic Profile
($V_{max} = 2\, V_{avg}$):
$\mathbf{u(r) = V_{max}\, [1 - (r/R)^2]}$
Turbulent Flow: Modeled using the empirical 1/7th Power Law for smooth pipes:
$\mathbf{u / V_{max} = (1 - r/R)^{1/7}}$

III. Darcy Friction Factor (Part 3)
The frictional resistance (f) was plotted against Re using the appropriate established correlations:
Laminar Flow: $\mathbf{f = 64 / Re}$
Turbulent Flow (Blasius): $\mathbf{f = 0.316 / Re^{0.25}}$

2. Visualization and Interactive Tools

MATLAB was used to generate log-log plots for frictional analysis and comparative velocity plots (both absolute and normalized by V_{avg}).
The interactive calculator uses a hybrid architecture that separates logic and interface. The core Re computation is performed by the MATLAB analytical engine. A Node.js server acts as a communication bridge, receiving inputs and sending them to MATLAB for processing, ensuring a seamless, cross-platform user experience (Part 4).
Streamlines were generated using MATLAB's streamslice function to visually represent the conceptual flow states (Part 5).

3. Computational Fluid Dynamics (CFD) Simulation

For the bonus component, a CFD simulation was performed using OpenFOAM (Open Field Operation and Manipulation) to compare high- and low-Re flow behavior.
Case Setup: The classic Lid-Driven Cavity Flow problem was simulated, where motion is induced by the velocity applied tangentially to the top wall.
Turbulence Modeling: For the high-Re simulation, a suitable Reynolds-Averaged Navier-Stokes (RANS) model (such as the k–ε model) was employed to resolve the time-averaged turbulent flow field and demonstrate intense momentum transfer and recirculation.
The results were visualized using ParaView.

Part 1: Reynolds Number Calculator and Regime Classification

- A database of different fluids was created, including water-in a different tempterature, air, blood, and cerebrospinal fluid (CSF) .

Reynolds numbers were calculated using the formula:

$Re = (\rho \times V \times D) / \mu$

where:

ρ = fluid density (kg/m^3)

V = mean velocity (m/s)

D = pipe diameter (m)

μ = dynamic viscosity (Pa·s)

The results were classified as:

- Laminar flow: $Re < 2000$
- Transitional flow: $2000 \leq Re < 4000$
- Turbulent flow: $Re \geq 4000$

Results interpretation

(figure 1.1) :

Reynolds Number Calculation and Regime Classification

The computational script successfully calculated the Reynolds Number (Re) for various fluids and flow configurations, classifying the regime based on the established criteria (Laminar < 2000, Transitional 2000 ≤ Re < 4000, Turbulent ≥ 4000). The selected sample results, displayed in the table below, highlight the critical dependence of Re on fluid properties (ρ, μ) and flow conditions (D, V).

Sample Results (Selected to show fluid and regime variation):

Fluid	Density	Viscosity	Diameter	Velocity	Reynolds	Regime	Type
{'Air at 20°C' }	1.204	1.825e-05	0.005	0.01	3.2986	{'Laminar' }	{'Newtonian' }
{'Air at 20°C' }	1.204	1.825e-05	0.01	5	3298.6	{'Transitional'}	{'Newtonian' }
{'Air at 20°C' }	1.204	1.825e-05	0.025	5	8246.6	{'Turbulent' }	{'Newtonian' }
{'Blood (37°C)' }	1060	0.0035	0.005	0.01	15.143	{'Laminar' }	{'Non-Newtonian'}
{'Blood (37°C)' }	1060	0.0035	0.005	2	3028.6	{'Transitional'}	{'Non-Newtonian'}
{'Blood (37°C)' }	1060	0.0035	0.005	5	7571.4	{'Turbulent' }	{'Non-Newtonian'}
{'CSF (37°C)' }	1007	0.0008	0.005	0.01	62.938	{'Laminar' }	{'Newtonian' }
{'Glycerin (20°C)'}	1260	1.41	0.005	0.01	0.044681	{'Laminar' }	{'Newtonian' }
{'Honey (20°C)' }	1420	10	0.005	0.01	0.0071	{'Laminar' }	{'Newtonian' }
{'Water at 20°C' }	998	0.001002	0.005	0.01	49.8	{'Laminar' }	{'Newtonian' }
{'Water at 20°C' }	998	0.001002	0.005	0.5	2490	{'Transitional'}	{'Newtonian' }
{'Water at 20°C' }	998	0.001002	0.005	1	4980	{'Turbulent' }	{'Newtonian' }
{'Water at 40°C' }	992	0.000653	0.005	0.01	75.957	{'Laminar' }	{'Newtonian' }
{'Water at 5°C' }	1000	0.001518	0.005	0.01	32.938	{'Laminar' }	{'Newtonian' }

figure 1.1

1. The Dominance of Viscosity (Fluid Properties)

The sample demonstrates the overwhelming impact of Dynamic Viscosity (μ) on flow regime, especially when flow conditions are minimal ($D = 0.005$ m, $V = 0.01$ m/s):

High Viscosity Fluids:

Fluids like Honey ($\mu = 10.0$ Pa·s) and Glycerin ($\mu = 1.41$ Pa·s) yielded extremely low Re values ($Re = 0.0071$ and $Re = 0.044$, respectively).

This confirms that their powerful viscous forces completely suppress inertia, ensuring the flow remains laminar under virtually any realistic conditions.

Biofluids Contrast:

Even with similar densities, the Re values differ significantly.

Blood ($\mu = 3.5 \times 10^{-3}$ Pa·s) maintained a low Re of 15.14 (Laminar), while Water at 20 °C ($\mu = 1.002 \times 10^{-3}$ Pa·s) had a Re of 49.8.

This contrast shows why flow in many small blood vessels (microcirculation) is overwhelmingly laminar, preserving the delicate endothelial layer.

Temperature Effect:

The minor variation in Re for Water at 5 °C ($Re = 32.94$) versus Water at 40 °C ($Re = 75.96$), holding D and V constant, illustrates that even small changes in temperature (which affects viscosity) are sufficient to alter Re.

2. Driving the Transition (Inertia Effects)

By holding the diameter constant ($D = 0.005$ m) and progressively increasing the velocity (V), the results clearly demonstrate the mechanism by which inertial forces overwhelm viscous forces, leading to transition:

Air Transition:

Due to its extremely low viscosity, Air at 20 °C transitions very quickly.

Increasing the velocity and diameter shifts the regime from Laminar ($Re = 3.3$) to Transitional ($Re = 3298.6$) by increasing V to 5.0 m/s and D to 0.01 m, and finally to Turbulent ($Re = 8246.6$) with a larger pipe.

Blood Transition:

The table shows that Blood transitions from Laminar ($Re = 15.14$) to Transitional ($Re = 3028.6$) and then Turbulent ($Re = 7571.4$) solely by increasing the velocity (V) from 0.01 m/s to 5.0 m/s within the small 5 mm pipe.

This is critical in biotransport, showing that turbulent flow is possible in major arteries during strenuous activity or certain pathological conditions.

In summary, the computational tool verified that the Reynolds number (Re) serves as a robust indicator of flow behavior, with viscosity dominating laminar flow and the product of velocity and diameter dictating the onset of the turbulent regime.

Part 2: Flow Profile Visualization

The theoretical velocity profiles for laminar and turbulent flows were plotted:
Laminar (parabolic):
$v(r) = 2 \times Vavg \times (1 - (r / R)^2)$
Turbulent (1/7th power law):
$v(r) = Vavg \times (6 / 7) \times (1 - |r| / R)^{1/7}$
Comparative plots were generated to visualize the differences in shape and velocity distribution.

Results Interpretation

figure 2.1
Physical regime: Clearly laminar (Re < 2000).
Blue curve (parabolic, laminar): Represents the expected real profile. The centerline (maximum) velocity is about V_max ≈ 200 cm/s (2.0 m/s), which is twice the mean velocity (V_max = 2 × V_avg).
Red curve (turbulent): Shows the profile that would occur if the flow were turbulent; here V_max would be lower (≈ 125 cm/s) and not double the mean.

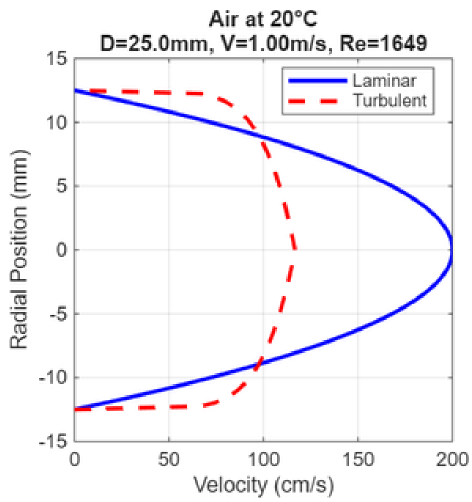


figure 2.1

figure 2.2

Physical regime: Turbulent (Re ≥ 4000). Even though the mean velocity is small, the low viscosity of water combined with the larger diameter yields a turbulent Re.
Red curve (turbulent): Represents the actual expected profile. It is blunt/flat and the centerline velocity is much closer to the mean (V_max ≈ 12 cm/s), substantially less than 2 × V_avg (which would be 20 cm/s).
Blue curve (laminar): Hypothetical laminar profile that does not occur; if laminar, V_max would be 20 cm/s.

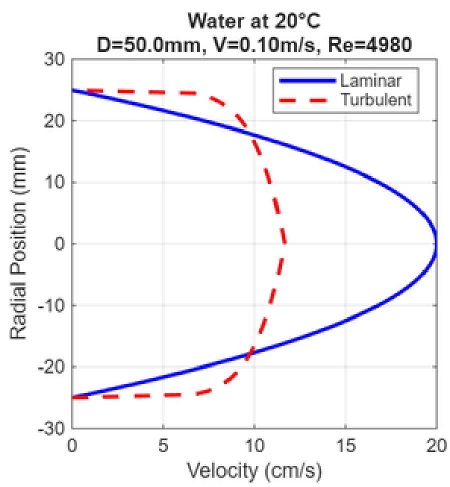


figure 2.2

figure 2.3

Physical regime: Transitional or near-turbulent (Re = 3299).
Effect of doubling velocity: Doubling V_avg from 1.00 m/s to 2.00 m/s doubles Re (1649 → 3299).
Blue curve (parabolic): If laminar, V_max = 400 cm/s (4.0 m/s), i.e., 2 × V_avg.
Red curve (turbulent): Shows a flatter profile with V_max around 250 cm/s — lower than the laminar prediction and indicating the onset of turbulence.

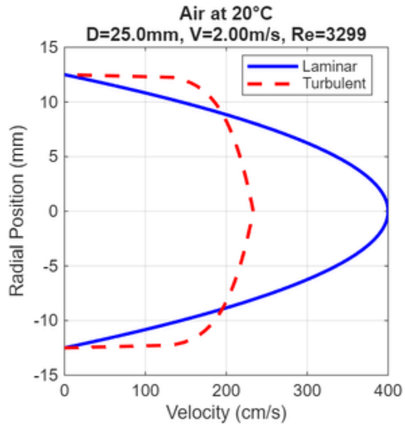


figure 2.3

Part 3: Reynolds Number Effects

The relationship between the Darcy friction factor (f) and Reynolds number (Re) was plotted using the following models:

Laminar: $f = 64 / Re$

Turbulent (Blasius): $f = 0.316 / Re^{0.25}$

Turbulent (Colebrook Approximation): $f = 0.11 \times (68 / Re + 0.0002)^{0.25}$

A logarithmic plot was created to show the clear distinction between laminar and turbulent regions, highlighting the transition zone.

Results interpretation

figure 3.1

Friction Factor (f) vs. Reynolds Number (Re)

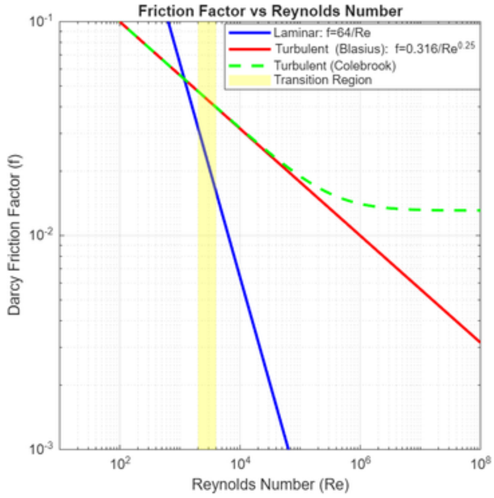


figure 3.1

This log–log plot illustrates how the fluid's resistance to flow (f) changes dramatically as the flow regime is determined by the Reynolds Number (Re):

1. Laminar Region (Re < 2000)

Line: Blue — $f = 64 / Re$

Meaning:

Shows a steep inverse linear relationship.

Resistance comes purely from viscous forces.

As Re increases, the relative influence of viscosity rapidly decreases, causing f to drop sharply.

2. Transition Region ($2000 \leq Re < 4000$)

Area: Yellow shaded region

Meaning:

The flow is unstable and unpredictable, oscillating between laminar and turbulent states.

This zone is avoided in engineering design because f cannot be reliably predicted.

3. Turbulent Region ($Re \geq 4000$)

Line: Red — Blasius: $f = 0.316 \times Re^{-0.25}$

Meaning:

The relationship is still inverse but much less steep.

Resistance is dominated by inertial forces and turbulent eddies (mixing), not just viscosity.

The influence of Re on f is much weaker than in the laminar regime.

4. Rough Pipe Line (High Re)

At very high Re, f becomes constant (horizontal).

Resistance depends solely on the pipe surface roughness, becoming independent of Re.

Conclusion

The Reynolds Number fundamentally shifts the energy loss mechanism — from being viscosity-dependent (laminar) to inertia-dependent (turbulent).

figure 3.2

Velocity profile vs Reynolds Number (Re)

Velocity Profile Overlap
The plot shows only two distinct profiles due to physical model limits and normalization:
Laminar Flow (Re = 500):
Has a parabolic shape, clearly different from turbulent profiles.
Turbulent Flow (Re ≥ 5000):
All turbulent profiles share the same Normalized Velocity relative to the Average Velocity **V / V**$_{avg}$ (e.g., Power Law).
Normalization Effect:
When profiles are normalized by the average velocity (V_{avg}), small differences disappear.
The lines overlap, leaving only the last one drawn (Re = 50000) visible.
Conclusion:
The profile shape is sensitive to the Laminar–Turbulent transition, but insensitive to Re once the flow becomes fully turbulent.

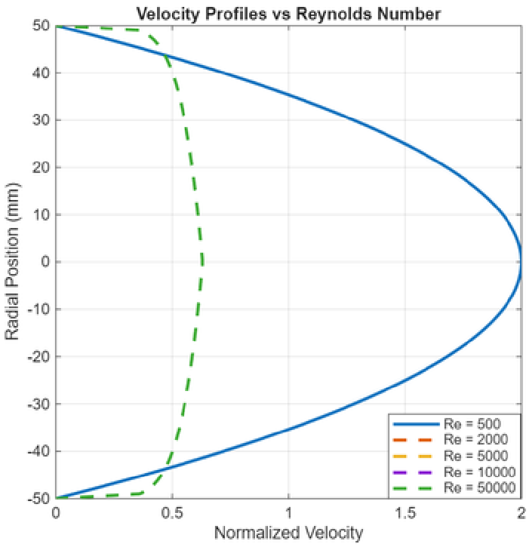


figure 3.2

Velocity Relationship in Pipe Flow
In fluid dynamics, the relationship between the maximum velocity (V_{max}) at the center of the pipe and the average velocity (V_{avg}) depends on the Reynolds Number (Re), which determines the flow regime:

Laminar Flow (Re < 2000)
Relationship:
$V_{max} = 2 \times V_{avg}$
Reason:
The velocity profile is parabolic.
Viscous forces dominate, smoothly transmitting wall friction toward the center.
To maintain a constant flow rate, the fluid at the center moves twice as fast as the average velocity.

Turbulent Flow (Re ≥ 4000)
Relationship:
$V_{max} < 2 \times V_{avg}$ (typically $1.25–1.4 \times V_{avg}$)
Reason:
The velocity profile is flatter (blunt).
Inertial forces dominate, creating chaotic eddies that mix momentum.
This mixing makes the near-wall flow faster and the center slower, leading to a lower V_{max} / V_{avg} ratio.

Part 4: Interactive Reynolds Number Calculator

The implementation of the Interactive Reynolds Number Calculator required a hybrid architecture to demonstrate advanced integration capabilities. Instead of using a standard MATLAB GUI, the calculator was built using the following technology stack:

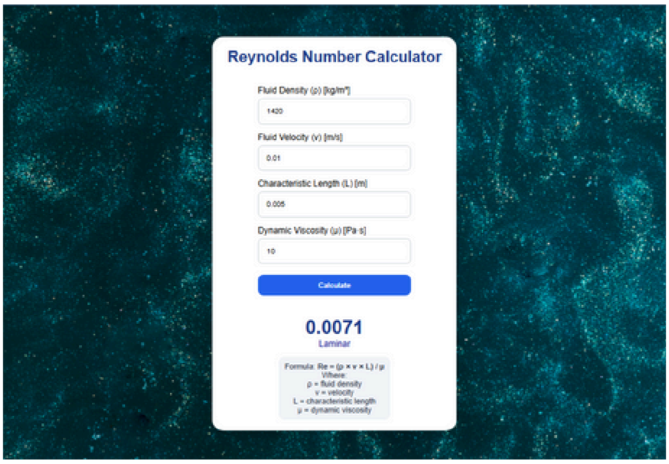
- Front-End / GUI:
- A custom graphical user interface (GUI) was developed to accept user inputs — Density (ρ), Dynamic Viscosity (μ), Velocity (V), and Characteristic Length (D).
- Back-End / Server:
- Node.js was utilized to create a lightweight, cross-platform server that manages communication between the GUI and the MATLAB core logic.
- To enable communication between the web interface and the MATLAB core logic, a Node.js server was used as a middleware layer. The server executes the MATLAB function through command-line calls, passing the input parameters received from the frontend. MATLAB processes the data and prints the computed output back to the command line. Node.js captures this output, formats it, and sends the final result to the frontend for display. This workflow allows seamless integration between the web application and MATLAB's computational engine.

This architecture ensures smooth, asynchronous communication and a clear separation between the core computational logic and the presentation layer, enabling scalability and cross-platform compatibility.

High Viscosity (Laminar Case):

As demonstrated by the input for Honey ($\rho = 1420$ kg/m³, $\mu = 10$ Pa·s) with a velocity of 0.01 m/s the calculation yields an extremely low Re = 0.0071.

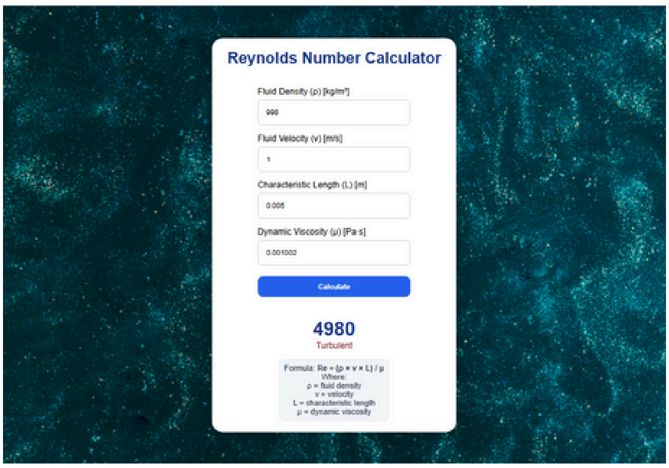
This value is highly dominated by viscous forces, resulting in an immediate Laminar classification.



Low Viscosity (Turbulent Case):

Conversely, inputting properties for Water at 20°C ($\rho = 998$ kg/m³, $\mu = 0.001002$ Pa·s) with a velocity of 1 m/s yields Re = 4980.04.

This value exceeds the critical threshold of 4000, confirming the transition to a Turbulent regime.



Part 5: Flow Regime Concepts

Streamline and quiver plots were used to visualize fluid motion:
how fluid motion changes as the Reynolds Number (Re) increases, transitioning the flow's dominant forces from viscous to

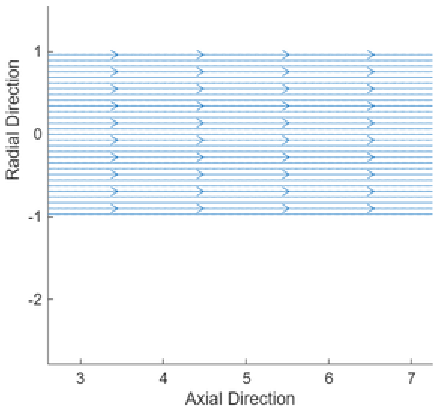


figure 5.1

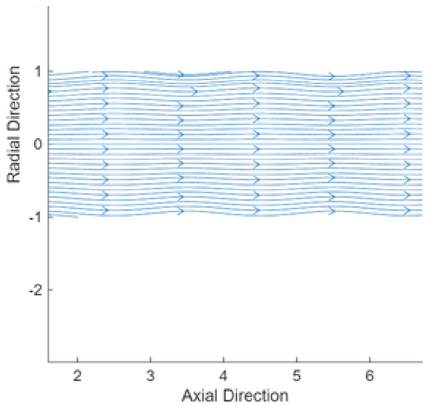


figure 5.2

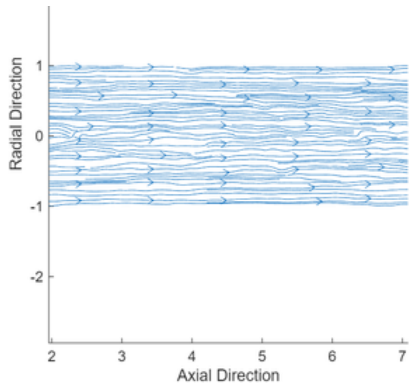


figure 5.3

Laminar Flow (Re<2000)
The streamlines are perfectly straight, parallel, and smooth, showing no mixing or crossing. This confirms that viscous forces dominate, causing the fluid to move in distinct, orderly layers (laminae) where energy loss is minimal and friction is purely viscous.

Transitional Flow (2000≤Re<4000)
The streamlines appear wavy and slightly disturbed. This instability signifies that inertial and viscous forces are nearly equal, causing the flow to oscillate between smooth, laminar behavior and chaotic, turbulent bursts. The slight deviations represent the initial formation of eddies.

Turbulent Flow (Re≥4000)
The streamlines are chaotic, tangled, and cross frequently, showing a high degree of randomness. This visualization confirms that inertial forces dominate, leading to intense mixing and the creation of eddies (vortices). This chaotic motion results in much higher energy loss and increased resistance to flow compared to the laminar regime.

Part 6 :Simulating Laminar and Turbulent Flow using OpenFOAM

Results Interpretation

figure 6.1 laminar case:

with a low Reynolds number (Re). The flow is dominated by viscous forces, resulting in a smooth, stable velocity field and a single primary vortex formed at the center. The motion of the top lid transfers momentum gradually through the fluid, while velocity decreases near the stationary walls due to the no-slip condition. The flow remains steady and symmetrical, which is characteristic of laminar behavior.

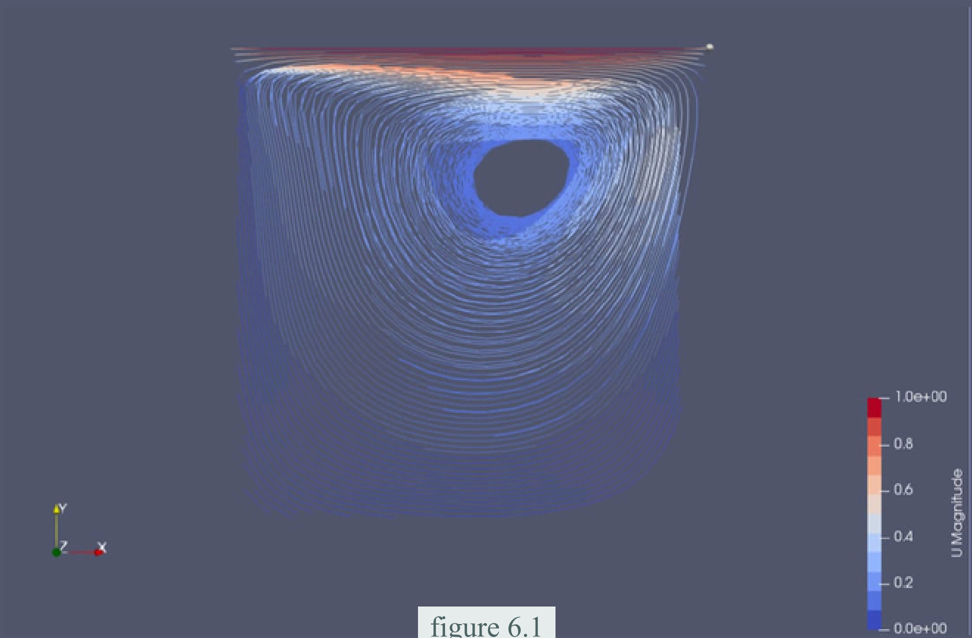


figure 6.1

figure 6.2 Turbulent Case :

When the Reynolds number was increased tenfold, the flow transitioned into a turbulent regime. The motion became highly unstable and irregular, characterized by multiple vortices, fluctuating velocity magnitudes, and chaotic eddy formations throughout the cavity. The influence of inertial forces dominated over viscous effects, leading to enhanced momentum transfer and mixing within the fluid. The velocity gradients near the walls became sharper, and the flow field lost the symmetry observed in the laminar case. This behavior is typical of turbulent flow, where energy dissipates through complex vortex interactions.

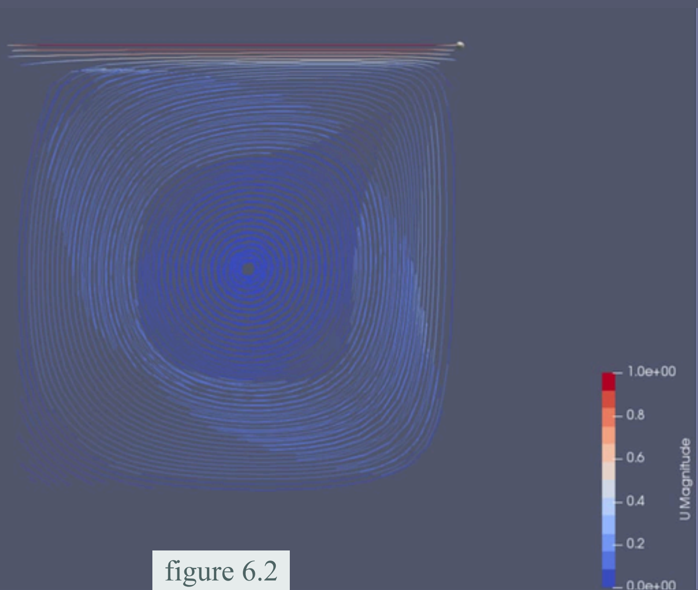


figure 6.2

5. Conclusion

This project successfully demonstrated the central role of the Reynolds number in predicting and understanding fluid flow regimes. Through computational modeling, theoretical analysis, and visualization, the following key conclusions were drawn:

- The Reynolds number accurately distinguishes between laminar, transitional, and turbulent flow.
- Flow behavior strongly depends on the fluid's viscosity, velocity, and pipe diameter.
- Laminar flow exhibits smooth parabolic profiles, while turbulent flow has flatter, mixed velocity distributions.
- The Darcy friction factor decreases as Re increases, showing different regimes of fluid resistance.
- The interactive MATLAB calculator serves as a practical educational tool for engineers and biomedical scientists.

Overall, this study enhances comprehension of fluid mechanics principles crucial in both engineering design and biomedical flow systems, providing a foundation for advanced simulations and CFD analyses.

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