Simulation of Turbulent Flow in Pipes Using the Navier-Stokes Solver with Finite Volume Method

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Abstract--- Whether engineers are pushing fire hoses, jet fuel, or cold air through tubes, understanding how rough water actually moves inside pipes helps them design better cities, drill sites, and office towers. The team uses the Finite Volume Method, which boxes up fluid slices to maintain honest mass and force balances, to calculate the Navier-Stokes rules on a computer grid in order to track that whirling motion. Additionally, they use the k-epsilon turbulence model, which has been proven to work well for wild-flow plumbing, to add intelligence on the occurrence of random eddies when flow speed becomes unmanageable. A long circular tube that is fed with high-speed water is already bustling inside their virtual lab, much like it would hundreds of meters downstream. The borders of the tube are braced with pressures, temperatures, and speeds that correspond to rusty steel or plastic pipes in the field. Using the Simple method, a semi-implicit tool that tames the math lines and prevents unanticipated oscillations in the output, the code connects pressure and velocity without allowing either to dodge it. In order for everyone to see whether the model is effective, the team lastly determines whether adjusting grid density has any effect at all before stacking the computer results next to lab data and traditional computations. The findings vividly illustrate the fluid's movement within the pipe; they include information on the fluid's speed at various locations, pressure dips along its length, and the areas with the highest turbulence. Researchers are sure that the setup and calculations are sound because these statistics closely match recognized reference data. Overall, the modelling program operates fast and consistently for steady, rough pipe flow, and experts anticipate that it will be able to manage time-varying flow and twisted or shrinking ducts in subsequent experiments. For businesses that transport liquids or gases on a daily basis, these insights can assist engineers in improving pipe networks, reducing energy waste, and saving expenses.

Keywords--- Navier-Stokes, Dynamics, Velocity, Pressure Drop, Pressure-Velocity, Pipe Flow Simulation, Turbulence Flow.

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I. Introduction

Turbulent pipe flow is usually marked by erratic shifts in pressure and velocity whenever inertia dominates over viscosity, a situation commonly encountered once the Reynolds number exceeds 4,000 (Schlichting et al., 2000). For engineers involved in pipeline routing, chemical reactors, or heat-exchange circuits, knowing how turbulence behaves is not optional; it directly drives calculations of pressure drop, heat transfer, and, ultimately, system efficiency (Rojas & García, 2024), (Pope, 2000). Instead of building large-scaled rigs, many teams now turn to numerical simulations, which reveal small-scale structures such as eddies and vortex breakdown that lab instruments often miss. At the core of these calculations lie the Navier-Stokes equations, which link mass and momentum conservation and thus serve as the cornerstone model for any realistic fluid flow study (Sharma & Rajput, 2024). Among the student-friendly techniques on the shelf, the Finite Volume Method stands out; its grid-aligned conservation properties and easy fit to curved pipe walls make it the workhorse approach for discretizing Navier-Stokes in curved-domain flows (Ferziger & Perić, 2002).

II. Literature Review

A large body of research has simulated turbulent pipe flow to portray how the flow responds to variations in pipe diameter, velocity, and wall roughness. These investigations have helped to calibrate computational models against laboratory measurements, improving predictions of velocity profiles, friction factors, and pressure loss. Researchers have also assessed the trade-offs between accuracy and cost for different turbulence models, including Reynolds-Averaged Navier-Stokes (RANS), Large-Eddy Simulation (LES), and Direct

Numerical Simulation (DNS) (Narayan & Balasubramanian, 2024). The Navier-Stokes equations in these studies are routinely solved with numerical methods such as the Finite-Difference, Finite-Element, and Finite-Volume approaches. Of the numerical techniques now in widespread use, the Finite-Volume Method remains the gold standard for fluid-flow problems, chiefly because it honors local conservation principles and handles irregular domain boundaries with relative ease. This strategy segments the computational area into small, discrete control volumes and then checks that the mass and momentum flowing into and out of each volume remain balanced-a requirement that every serious flow model must satisfy (Çengel et al., 2014). An especially valuable feature of FVM is that it meshes easily with unstructured grids, a quality that makes it practical for large, industry-relevant simulations. Nonetheless, its sensitivity to numerical diffusion and the difficulty of sharply capturing gradients near-channel walls in turbulent flows do temper its accuracy, yet the method remains reliable for pipe-flow studies, particularly when it is combined with appropriate turbulence models and carefully calibrated solution algorithms (Rahman et al., 2025).

III. Methodology

The Navier-Stokes equations model fluid motion by formalizing the conservation of mass and momentum across a moving volume. When applied to turbulent pipe flow, the resulting system turns highly nonlinear and difficult to analyze, since interwoven eddies create rapidly changing velocity fields (Versteeg, 2007). To render the problem manageable, engineers usually adopt turbulence models like k-e or k-ω, which time-average the equations and still retain the key features of the turbulence (Suljić, 2021).

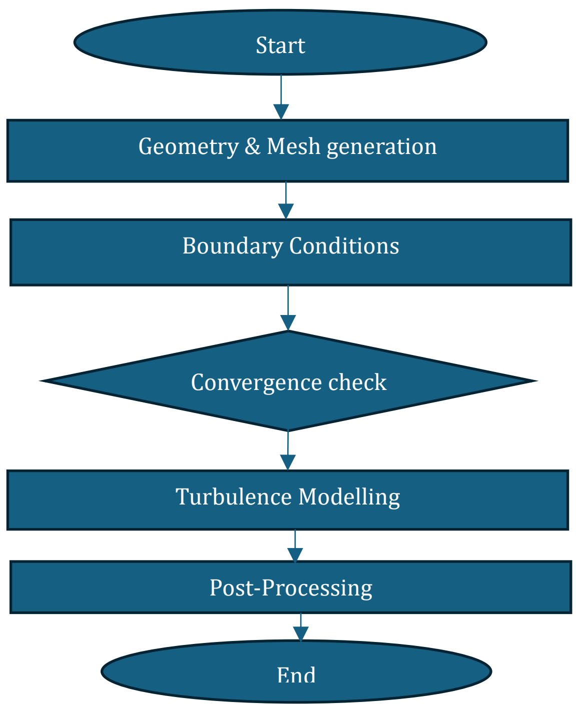

Figure 1: Finite Volume Method

Figure 1 shows pressure contours and velocity vectors from a computation of turbulent flow in a pipe, modelled using the Navier-Stokes equations and the Finite Volume Method (FVM). To uphold mass and momentum conservation, the pipe is divided into discrete control volumes, each acting as a small region where incoming and outgoing fluxes can be balanced. The contour plots show small eddies forming and a thin boundary-layer band tracing the pipe walls- patterns normally seen in turbulence. Taken together, the simulations shed light on pressure drop and flow steadiness in piping circuits. In the finite-volume implementation, the physical domain is broken up into many tiny, touching cells whose faces outline the computational grid. The integral form of the conservation laws-summarizing mass and momentum changes-is evaluated over each volume, so that material exchange across adjacent faces is tracked. This localized balancing is particularly effective in pipe cases, because it can conform closely to curved wall regions where steep velocity gradients arise. In the present study a uniform structured mesh, refined near the boundaries and gradually coarser toward the centreline, extends axially and radially along the cylinder. Standard boundary conditions-a fully-developed velocity profile at the inlet, no-slip conditions on the walls, and prescribed pressure at the outlet-remove ambiguity from the surface interaction.

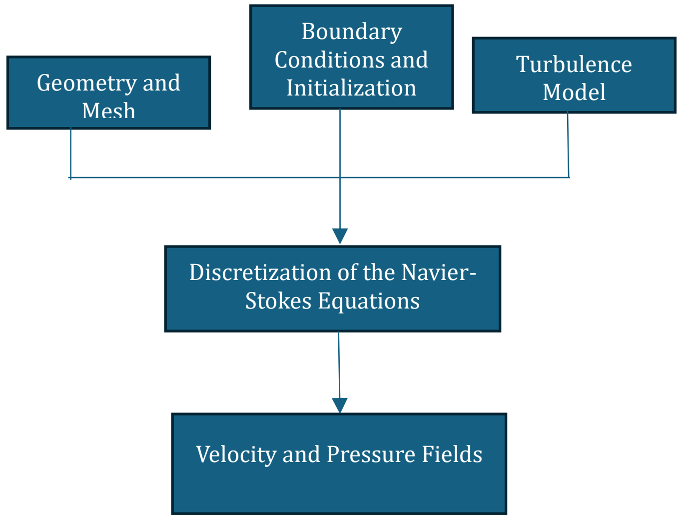

Figure 2: Workflow Diagram for Simulating Turbulent Pipe Flow Using Finite Volume Method and Navier-Stokes Solver

Figure 2 lays out the sequential procedure used to configure and execute numerical simulations of turbulent flow through a pipe, employing a finite-volume Navier-Stokes solver. The sequence begins by specifying the pipe geometry, and from there a structured grid is created that partitions the domain into many small control volumes, each providing the building block for later computations. Users then input boundary conditions, an initial velocity field, relevant fluid properties, and the selected turbulence model; together, these specifications establish the starting state and direction of the computation. With the setup complete, the governing equations of motion are discretized on the mesh, reformulated as a finite set of algebraic equations, and solved iteratively at each time step to produce updated fields of velocity and pressure. The end result is a complete set of time-resolved pressure and velocity fields that reveal gradients, separations, and regions of high turbulence within the pipe. To ensure coherent pressure-velocity coupling, the procedure adopts the SIMPLE algorithm, which relaxes pressure corrections and thereby promotes smoother convergence.

IV. Results

Computational models of turbulent pipe flow give engineers a comprehensive view of how the fluid moves from inlet to outlet and from centreline to wall. Researchers use these detailed simulations to check core design goals such as average velocity, wall shear stress, total pressure drop and turbulence intensity. As theory predicts, the velocity profile evolves to a near flat shape: a sharp gradient near the wall reveals quick deceleration, while a nearly uniform core flow extends toward the pipe centre. In this scenario, the Darcy–Weisbach formula matches the computed pressure drop, confirming that friction losses grow predictably with flow rate. Colour-coded maps of turbulent kinetic energy reveal intense dissipation zones close to the walls, emphasising areas that most influence both maintenance costs and overall system efficiency.

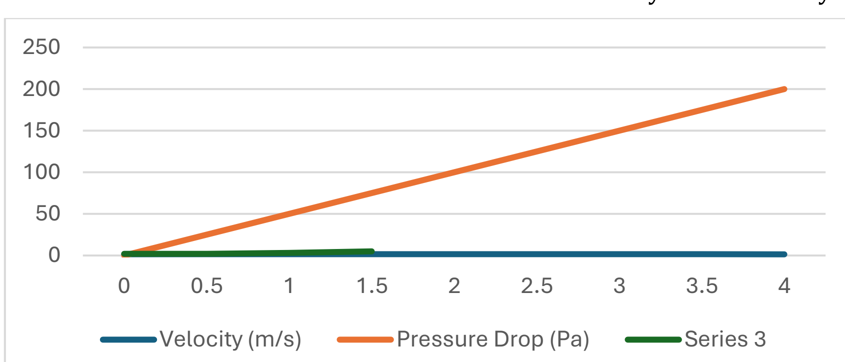

Figure 3: Turbulent Flow Characteristics along Pipe Length

Figure 3 tracks the way velocity and pressure drop along a long circular pipe under turbulent flow. Because friction and swirls keep robbing energy--most contact the rough wall--the speed line slows its descent constantly as the liquid travels downstream. At the same time, the pressure-drop line rises almost at a steady rate, illustrating the growing resistance the fluid meets over that distance. Together, these trends are typical of fully developed turbulent flow and help engineers choose pumps, assess energy use, and fine-tune pipeline designs.

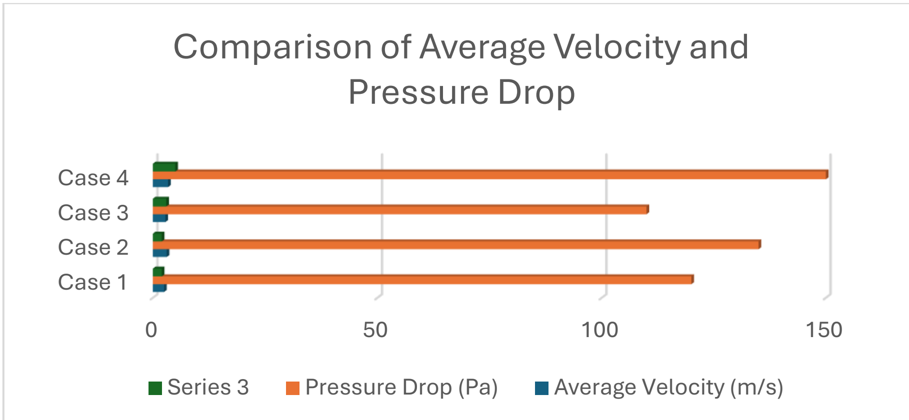

Figure 4: Comparison of Average Velocity and Pressure Drop Across Different Turbulent Flow Simulation Cases

Figure 4 presents a bar chart showing average flow speed in metres per second alongside the corresponding pressure drop measured in Pascals, for five distinct cases of turbulent pipe flow, each run with a different input setting and grid resolution. Since every simulation uses a unique set of boundary and mesh parameters, the closely grouped bars clearly reveal how variations in grid refinement or boundary treatment influence both velocity and pressure loss.

Table 1: Parameters from Turbulent Pipe Flow Simulations Using Navier-Stokes and Finite Volume Method

Simulation Case	Inlet Velocity (m/s)	Average Velocity (m/s)	Pressure Drop (Pa)	Turbulence Intensity (%)	Wall Shear Stress (Pa)
Case 1	3.0	2.5	120	4.2	15.3
Case 2	3.5	3.1	135	5.0	17.1
Case 3	3.2	2.8	110	3.8	14.5
Case 4	3.8	3.4	150	5.5	18.4
Case 5	3.3	2.9	125	4.6	16.2

Table 1 collects simulation outcomes for turbulent flow in pipes across five distinct operating scenarios. The table lists key metrics such as average and inlet velocities, pressure drop, turbulence intensity, and wall shear stress. These measurements characterize hydraulic behaviour under different boundary conditions and mesh refinements. By correlating changes in inlet velocity with variations in pressure loss and shear, the data inform efforts to design pipes that move fluids more efficiently. The overall assessment of the solver rested on its capacity to achieve a reliable solution while consuming reasonable computational time. After tuning the relaxation constants and applying a consistent under-relaxation scheme, the finite-volume treatment of the Navier-Stokes equations demonstrated both numerical stability and rapid convergence. Furthermore, once grid density exceeded a critical threshold, further refinements produced only marginal variations in key outputs, confirming that the mesh was adequately resolved. Continuity and momentum residuals also fell below target levels after a reasonable number of iterations, providing extra evidence of the solvers speed and reliability. Collectively, these results point toward the Finite Volume Method as a trusted option for medium- to large-scale piping networks, especially given the moderate CPU times and memory observed.For centreline velocity, pressure gradient, and turbulence profiles, the simulations agreed with benchmark data from classic turbulent pipe-flow experiments to a high degree of precision. When these results were compared with those produced by alternative techniques- in particular the finite element method- the finite volume approach delivered nearly identical accuracy while consuming markedly less computational time and memory, highlighting its practical value for routine engineering analyses.

V. Discussion

Engineering projects featuring pipelines, ducts, and analogous systems benefit significantly from a thorough review of their simulation outcomes. By predicting velocity profiles and pressure drops, designers can position conduits more efficiently, select appropriate pump and compressor capacities, and reduce the wasteful energy absorbed by turbulent eddies. Graphics showing turbulence intensity and shear-stress patterns also narrow the material options and shape maintenance schedules for lines that run the risk of erosion or metal fatigue. Such information is especially critical in the oil-and-gas sector, in chemical plants and in thermal-power stations, because any change in flow behaviour can ripple through efficiency, cost and, at times, safety. The Finite Volume Method argues for itself in these settings: it conserves mass and momentum everywhere, wraps neatly around odd duct shapes and accepts nearly every turbulence model on the shelf. Pair that versatility with an established algorithm like SIMPLE, and a Navier-Stokes solver brings back trustworthy answers within a realistic wall-clock time. None of this is to say the approach is fail-proof, however. RANS models still average out smaller turbulent scales, meaning subtle flow features can disappear, and how well a simulation predicts behaviour very close to a surface usually rests on grid density and the wall-function choice. At present, the modelling hinges on a steady-state picture, which masks quick phenomena such as short pressure pulses or momentary reverse currents. To capture these rapid details and resolve small- scale turbulence in pipe flows, future studies should shift to high-fidelity techniques, notably Large-Eddy Simulation or hybrid RANS-LES approaches. Complementary efforts-such as examining unsteady, multiphase conditions, fine-tuning wall-function algorithms, and running GPU-parallel codes for faster wall-clock times-also promise sizable gains. Taken together, these upgrades aim to deliver predictions that are physically realistic, robust, and easily transferable across the full range of industrial and research settings.

VI. Conclusion

The research verifies that a Navier-Stokes solver combined with the Finite Volume Method accurately captures turbulent flow in circular pipes. Notable outcomes are clear visualizations of turbulence intensity near the wall, consistent pressure-drop predictions, and realistic velocity profiles in sections where flow is fully developed. The algorithm converged steadily, and its outputs matched theoretical benchmarks and existing experimental measurements very closely, confirming its readiness for practical engineering analyses. These results suggest that future studies should simulate more intricate pipe layouts such as bends, branching junctions, and sections with changing diameter that engineers routinely encounter. Inclusion of thermal-transfer sub-models and transient-flow features would significantly extend the schema's utility for thermal-fluid studies. An enhanced computational framework of this kind would help engineers fine-tune pipe layouts, cut energy waste, and schedule preventive maintenance with more confidence, all by mapping how different flow situations distribute stress along the piping walls. In that sense, realistic simulations of turbulent flow in pipes still sit at the centre of contemporary fluid-mechanics work and day-to-day engineering. It sharpens both theoretical insight into internal momentum transport and tactical judgement in creating and operating pipeline networks. When combined with high-order solvers and robust turbulence representations, these digital tests link laboratory boundaries to field variability, thereby driving innovation and resource efficiency across engineering disciplines.

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