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A comprehensive review of large eddy simulation techniques for turbulent pipe flows

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Abstract

Turbulent pipe flow is a common and significant configuration in fluid dynamics that is utilized as a benchmark for basic turbulence research and as a model for numerous engineering uses. Reynolds-Averaged Navier-Stokes (RANS) models are prevalent in industry; nevertheless, their inadequacy in adequately depicting complicated unstable processes has necessitated the adoption of more sophisticated methodologies. Large Eddy Simulation (LES) has evolved into an effective compromise, tackling the significant, energy-rich scales of motion while concurrently simulating the ubiquitous, minute scales. This review article looks at how LES has changed, how it is used, and what it has done for turbulent pipe flow. We discuss the primary methodologies, including Subgrid-scale (SGS) models, approaches for addressing near-wall effects, and numerical systems. An overview of the most essential facts LES taught us about turbulence statistics, coherent structures, and controlling flow. We also work on problems that keep coming up, such high computing costs, getting the near-wall resolution right, and simulating complex setups that involve heat transfer, roughness, and multiphase flows. to the end of the study, there is a look to the future of LES, with a focus on how stronger computers and new hybrid approaches will be used.

Keywords: Large Eddy Simulation; Turbulent Pipe Flow; Subgrid-Scale Modeling; Wall-Resolved Les; Wall-Modeled Les; Coherent Structures; Direct Numerical Simulation

1. Introduction

One of the fundamental issues in fluid mechanics is turbulent flow in pipes, which Osborne Reynolds first thoroughly examined in 1883 [1]. It is used in many engineering systems, such as chemical processing facilities, oil and gas pipelines, nuclear reactor cooling, and biological processes like blood circulation. For more than 100 years, there has been a great deal of experimental and computational research focused on the core features of fully developed turbulent pipe flow, including mean velocity profile, friction factor, Reynolds stress distributions, and coherent vortical structures.

A new paradigm for researching this flow was made possible by the development of computational fluid dynamics (CFD). At first, RANS models were the only practical choice. Their dependence on turbulence closure models, however, frequently results in inaccurate predictions of flow separation, severe unsteadiness, and curvature effects [2]. For engineering applications with high Reynolds numbers (Re), Direct Numerical Simulation (DNS), which resolves all turbulence scales without modeling, is unaffordable [3], [4].

This crucial void is filled by Large Eddy Simulation (LES). LES uses a subgrid-scale (SGS) model to simulate the effects of the smaller, more universal scales and explicitly calculates the large, geometrically dependent eddies by filtering the Navier-Stokes equations. For high-Re flows, this method has a computational cost much lower than DNS while providing a more accurate depiction of unsteady turbulence dynamics than RANS [5]. This review summarizes the vast amount of research that has been done on the application of LES to pipe flow, emphasizing its methods, achievements, and the special physical insights it has made possible.

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2. LES of Pipe Flows: A Methodological Framework

2.1. Governing Equations and Filtering

LES is based on the spatial filtering operation, which breaks down any flow variable ($\phi(x,t)$) into a residual (or subgrid-scale, SGS) component ($\phi'(x,t)$) and a resolved (or filtered) component ($\bar{\phi}(x,t)$):

$$\phi(x,t) \ = \ \bar{\phi}(x,t) \ + \ \phi'(x,t)$$

The resolved equations of motion can be obtained by applying this filter to the incompressible Navier-Stokes equations:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u_i}\overline{u_j}\right) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + v\frac{\partial^2 \overline{u_i}}{\partial x_i \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}$$

The SGS stress tensor, which needs to be modeled, is represented by

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\,\overline{u_j}$$

where $\overline{u_j}$ *and* $\bar{p}$ are the resolved velocity and pressure fields. The main problem of LES is this term, which denotes the momentum transfer between the resolved and subgrid scales.

2.2. Subgrid-Scale Models

Pipe flow simulations have used a wide range of SGS models, each with unique benefits and drawbacks.

2.2.1. *The Smagorinsky Model*

The most popular and traditional model, postulates that the SGS stress is proportional to the resolved strain-rate tensor $\overline{S_{ij}}$:

$$\tau_{ij} - \frac{1}{3}\tau_{kk} = -2v_{sgs}\,\overline{S_{ij}}$$

$$v_{sgs=(C_s\Delta)^2|\bar{S}|}$$

With C_s as the Smagorinsky coefficient and Δ as the filter width. Its primary limitations are its excessive dissipation in laminar or transitional regions and the requirement for empirical damping functions (such as van Driest damping) close to walls [5, 6].

2.2.2. *Dynamic Procedure*

Germano et al. [7] developed a ground-breaking dynamic approach that does not require pre-defined damping in order to compute $\overline{C_S}$ locally and instantaneously based on the resolved scales. Because it enables the model coefficient to adjust to laminar regions and near-wall effects [9], [10], this method—which Lilly further stabilized [8]—has become the norm for complex flows, including pipes.

2.2.3. *Mixed and Scale-Similarity Models*

Although they come at a higher computational cost, models such as the dynamic mixed model [12] and the scale-similarity model [11] have demonstrated increased accuracy in predicting the energy transfer between scales when combined with the eddy-viscosity model.

2.2.4. *Implicit LES*

The discretization scheme's numerical dissipation serves as an implicit SGS model in ILES. This method has demonstrated remarkable efficacy for wall-bounded flows, such as pipes, for high-order numerical methods on sufficiently fine grids. [13, 14].

2.3. Near-Wall Treatment and Grid Resolution

Because it controls wall shear stress and turbulence production, the near-wall region is crucial. Extremely fine grids are needed to resolve the steep velocity gradients. Wall units, where ν is the kinematic viscosity and $\overline{u_\tau}$ is the friction velocity, are frequently used to measure the resolution: $\Delta x\text{^}+ \approx$ 50 to 100 is the streamwise spacing. The azimuthal spacing is between 15 and 30 ($r\ \Delta\theta\text{^}+$). Wall-normal spacing: at the wall, $\Delta y\text{^}+ <$ 1.

Wall-Resolved LES (WRLES) simulations are very accurate, but their computational demands limit them to moderate Re [15], [16].

Engineering-scale Re is accessed using Wall-Modeled LES (WMLES). In this case, the outer LES receives the wall-shear stress from the inner layer (usually $y\text{^}+ <$ 100) which is not resolved but is modeled using a simplified model (such as a law-of-the-wall or a thin-boundary-layer equation solver). [17, 18]. Despite being computationally efficient, WMLES' accuracy is highly dependent on the wall model's fidelity, particularly in non-equilibrium flows.

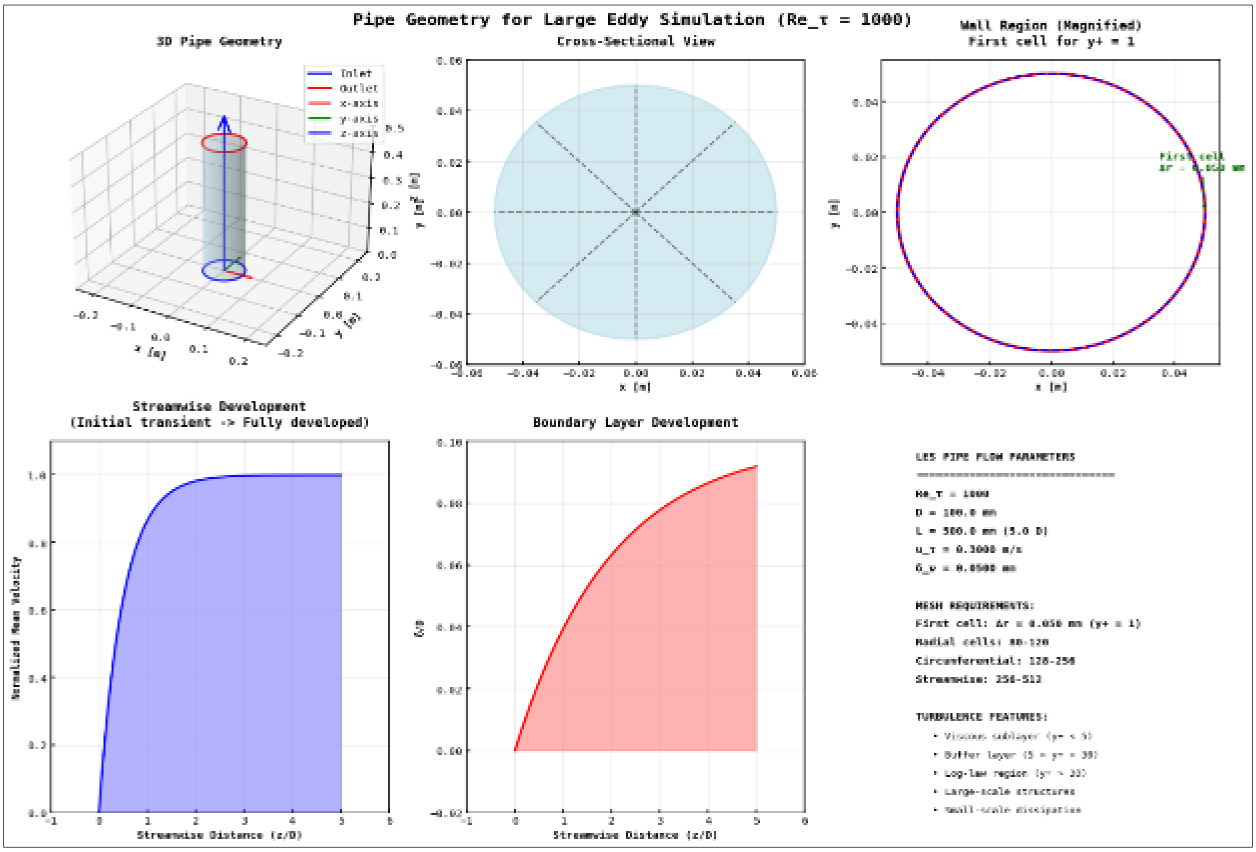

Figure 1 Pipe Geometry for Large Eddy Simulation

2.4. Boundary Conditions and Numerical Methods

Spectral methods have been the gold standard for DNS and high-fidelity LES of canonical pipe flows because they take advantage of the homogeneity in the azimuthal and streamwise directions [3], [19]. Finite-volume [21] and high-order finite-difference [20] methods are common for more complicated geometries.

For fully developed flow simulations, streamwise periodic boundary conditions are used. At the pipe wall, the no-slip condition is enforced. In order to produce physically realistic inlet conditions, methods such as recycling-rescaling [22] or synthetic turbulence generators [23] are crucial for producing inflow turbulence for developing flows.

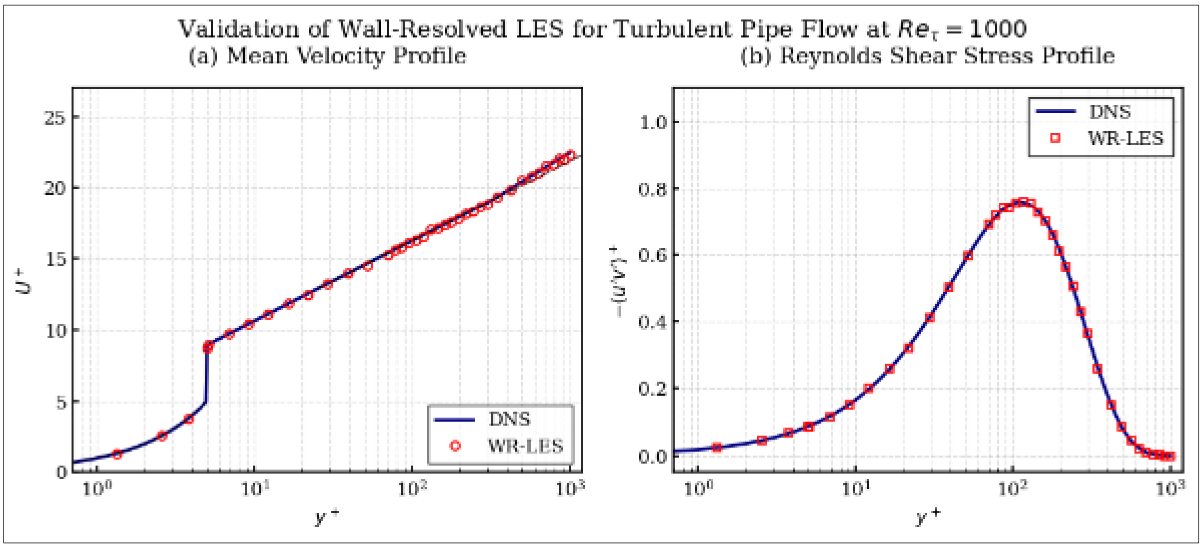

Figure 2 Validation of Wall-Resolved LES for Turbulent Pipe Flow at $Re_1 = 1000$

3. Key Insights from LES of Pipe Flows

LES has helped us understand more about turbulence in pipe flow and validate what we already understood.

3.1. Turbulence Statistics

LES has effectively replicated fundamental statistics of turbulent pipe flow, including the mean velocity profile (comprising the viscous sublayer, buffer layer, and logarithmic law), Reynolds stresses, and higher-order moments such as skewness and flatness [9], [16], and [24]. Dynamic LES has demonstrated its efficacy by accurately forecasting these values, even on coarser grids compared to DNS.

3.2. Coherent Structures

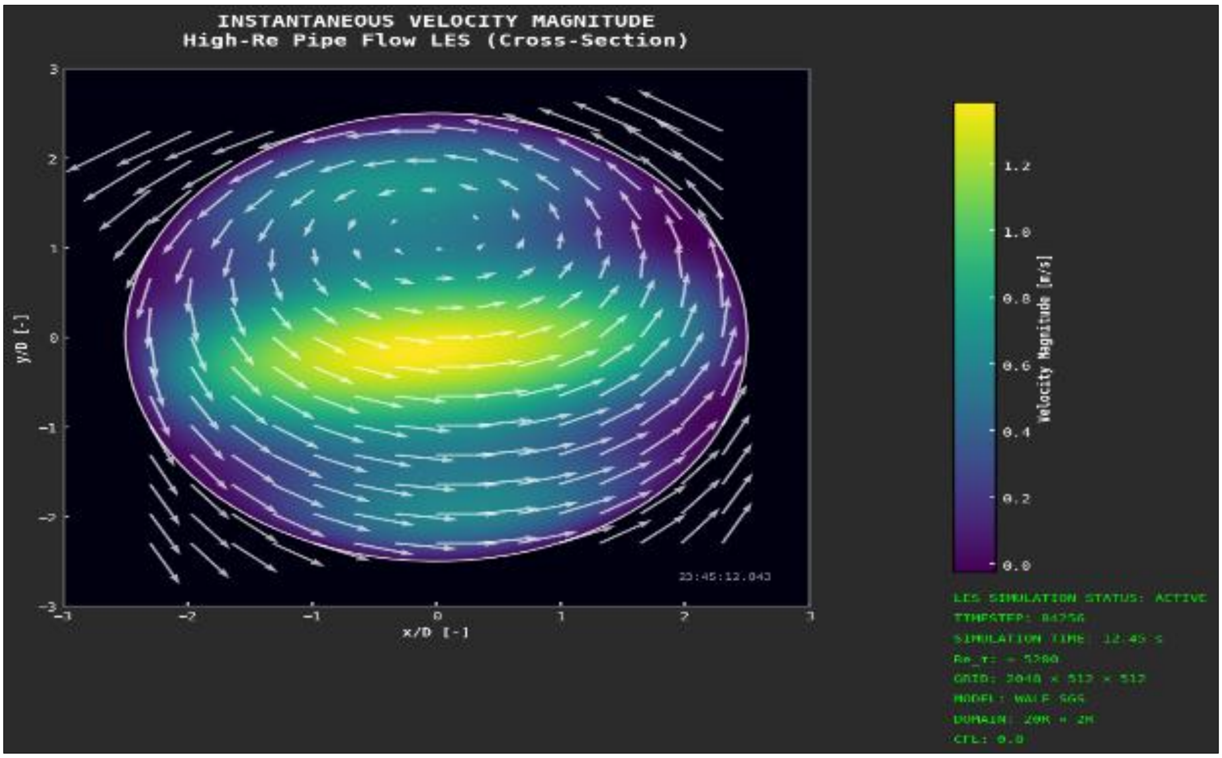

Figure 3 Instantaneous Velocity Magnitude

LES does an excellent job of displaying how structures that are cohesive alter over time. It has clearly shown how near-wall streaks grow up and break down, as well as the ejection and sweep events that are needed for turbulence to happen [25]. Researchers have employed Large Eddy Simulation (LES) to investigate substantial structures, such superstructures or very large-scale movements (VLSMs), which may extend 10 to 20 pipe radii in length and retain significant turbulent kinetic energy and Reynolds shear stress [26, 27].

The iso-surfaces of the Q-criterion are colored according on the speed of the flow. This illustrates a complicated hierarchy of coherent structures, from big movements in the log region to streaks along the wall.

3.3. Flow Control and Modified Flows

LES is a good way to learn about how to control flow. It has been used to learn:

- Drag Reduction: LES has been employed to conduct an exhaustive analysis of the impacts of additives (including polymers [28]), riblets, and active control strategies on drag and turbulence.
- Heat transport: RANS models often falter in this domain; however, LES, when combined with a filtered energy equation, can precisely forecast turbulent heat transport [29], [30].
- Effects of Roughness: LES demonstrates the impact of roughness on mean flow and turbulence, either by directly resolving the flow around rough surfaces or by employing roughness models to illustrate their effects on the flow [31].
- Rotating and Curved Pipes: LES does a fantastic job of showing the secondary flows and uneven turbulence that happen in systems that revolve [33] and pipes that curve [32].

3.4. Current Challenges and Future Scopes

LES of pipe flows has made some progress, but it still has a lot of issues to solve, such as

- Cost of Computing: WRLES is still hard to do when Re is high, like when $Re\varrho$ is more than 10,000. It costs about Re^(2.4) more to do computer work [34].
- Wall Modeling: Researchers are always looking into how to make wall models that are accurate and durable for complex flows with separation, strong pressure gradients, and heat transfer [17, 35].
- Inflow Conditions: It's still hard to make true turbulent inflow conditions for industrial use, which can have a big impact on the results of simulations [23].
- As for multiphase flows, it is harder to describe contact tracking and phase interactions when LES is used on multiphase pipe flows like bubbly flows and slurry transport [36].

Good things are coming for LES as computer power keeps going up, more and more people will use high-Re WRLES. There are possible ways to improve SGS and wall models with machine learning [37]. DES [38] and other hybrid RANS-LES methods will still be useful in industry, where RANS is used to deal with boundary layers that are connected and LES is used to deal with regions that are separated.

4. Conclusion

Large Eddy Simulation has become an important technique for studying turbulent pipe flow. It gives you insights into turbulence dynamics that you can't get with RANS or DNS at high Reynolds numbers and it strikes the perfect balance between cost and realism. By continued development of SGS modeling, wall modeling and numerical algorithms, LES will be an important tool for engineers who are developing and studying complex systems with internal flows, as well as for basic turbulence research.

Compliance with ethical standards

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Disclosure of conflict of interest

The author declares that there is no conflict of interest to be disclosed.

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