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Connecting Large Eddy Simulation and Reduced-Order Modeling of Convection-Dominated Flows via Spatial Filtering: A Review and Future Perspectives

Traian San*

Department of Mathematics, University of Houston, 3551 Cullen Blvd, Houston, TX 77204, USA

Introduction

In the field of computational fluid dynamics, the study of convection-dominated flows flows where convection dominates over diffusion presents significant challenges. These types of flows are commonly encountered in engineering applications such as heat exchangers, combustion chambers, and atmospheric dynamics. Modeling such flows with accuracy requires sophisticated approaches that can capture both large and small-scale turbulent structures. Two prominent computational techniques used to study these flows are Large Eddy Simulation and Reduced-Order Modeling. While LES resolves large turbulent eddies directly and models the effects of smaller scales, ROM focuses on simplifying the system's complexity by reducing its dimensionality, making simulations more efficient. However, these two approaches have distinct strengths and limitations. Large Eddy Simulation is a turbulence modeling approach where the large-scale motions of the fluid flow are directly resolved, and only the small-scale, subgrid motions are modeled. LES is particularly useful in simulating convection-dominated flows because it offers a high degree of accuracy for resolving the turbulent structures that are responsible for heat and mass transport [1-3].

Description

In LES, the flow field is typically decomposed into resolved scales and subgrid scales, which represent the smaller eddies that are too fine to be directly resolved by the computational grid. The resolved scales of LES provide detailed information on the larger turbulent structures, which is essential for accurate predictions in convection-dominated flows where these structures play a significant role in energy transport. The modeling of the SGS is typically done using a subgrid-scale model, which estimates the effects of unresolved turbulence on the resolved scales. However, while LES can provide detailed insight into turbulent flow, its computational cost can be prohibitively high. The need for very fine grids to resolve turbulent eddies can make LES computationally expensive, especially for large or complex systems, limiting its widespread application in real-world engineering problems. Reduced-Order Modeling aims to simplify complex fluid flow systems by reducing the number of variables and equations required for simulation, without significantly sacrificing accuracy. ROM techniques are particularly advantageous for convection-dominated flows because they provide a way to simulate these flows quickly and efficiently. Instead of resolving every single detail of the turbulence as in LES, ROM focuses on capturing the dominant features of the flow and using simplified models to describe the less significant dynamics [4,5].

***Address for Correspondence:** Traian San, Department of Mathematics, University of Houston, 3551 Cullen Blvd, Houston, TX 77204, USA; E-mail: sant@gmail.com*

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Conclusion

The combination of Large Eddy Simulation and Reduced-Order Modeling via spatial filtering represents a promising strategy for simulating convection-dominated flows. By resolving large turbulent structures with LES and simplifying smaller-scale dynamics with ROM, this hybrid approach provides an efficient and accurate means of studying complex flow systems. While challenges such as the accuracy-efficiency trade-off and subgrid-scale modeling persist, ongoing advancements in computational methods and hybrid modeling techniques hold the potential to further enhance the performance of LES-ROM coupling. With continued research, this approach may become a cornerstone in the modeling of convection-dominated flows across a wide range of scientific and engineering applications.

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Conflict of Interest

None.

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