Coarse-Grained Simulation Method for Turbulent Nonequilibrium Plasma Flows

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Nonequilibrium plasma flows in diverse applications often display instabilities and turbulence. The direct simulation of turbulent plasma flows is exceedingly expensive due to the large range of scales involved, which has motivated the development of coarse-grained simulation strategies. The Variational Multiscale-*n* (VMS_n) method is presented as a consistent and complete approach for the coarse-grained simulation of turbulent nonequilibrium plasmas. The method builds on the VMS framework and does not rely on the use of empirical or model/problem-specific parameters. Preliminary results confirm that VMS_n produces significantly more accurate results than VMS, comparable with state-of-the-art approaches for other types of flow problems.

1. Introduction

Nonequilibrium plasmas are at the core of diverse applications, from materials processing to medicine. Thermodynamic nonequilibrium (NLTE) is generally a consequence of the interaction of plasma with processing media. This interaction also incites diverse types of instabilities and often leads to turbulence. The direct computational simulation of turbulent plasmas is often unfeasible due to the wide range of scales involved, which prompts the need for coarse-grained simulation approaches. Large Eddy Simulation (LES), the standard coarse-grained approach for turbulent incompressible flows, largely relies on assumptions not valid for plasmas.

2. Nonequilibrium plasma flow model

The NLTE plasma flow model, described in [1], is constituted by a coupled set of two-temperature (heavy-species and electrons) fluid conservation and electromagnetic equations. The model is treated as a single system of transient-advective-diffusive-reactive equations, which allows its straightforward extension to accommodate other plasma models.

3. Variational Multiscale-*n* formulation

The Variational Multiscale-*n* (VMS_n) method is a consistent and complete approach for the simulation of turbulent flows without the need for empirical or model/problem-specific parameters. VMS_n is built on the VMS framework based on a variational decomposition of scales into *large* (grid-scale) and *small* (unresolvable) together with a residual-based approximation of the small scales [2]. A major challenge of VMS methods is the handling of the nonlinearity of the small scales, which VMS_n addresses by a fixed-point procedure [3]. The n in VMS_n indicates "nonlinear" or the level of approximation used, i.e., from $n = 0$ for the classical VMS method, to an exact description for $n = \infty$.

4. Method validation and next steps

Representative validation results are presented in Fig. 1 for the simulation of an incompressible turbulent free jet. The VMS_n results show significantly improved accuracy than VMS and comparable to those by the dynamic Smagorinsky method, the state-of-the-art LES approach, but without empirical or model/problem-specific parameters. On-going efforts include the validation of the VMS_n method with experimental data of the flow from a non-transferred arc plasma torch.

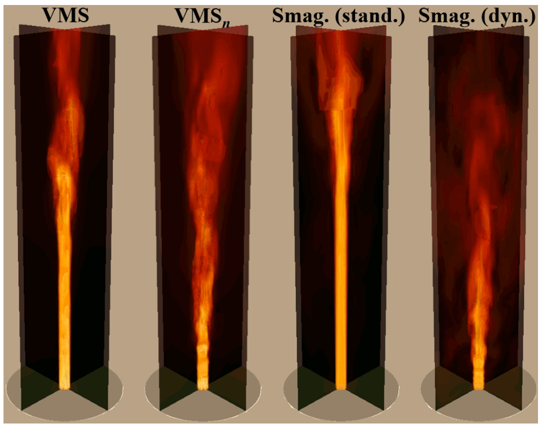

Fig. 1: Incompressible jet flow: instantaneous normalized velocity magnitude for different methods.

Acknowledgements: This work has been founded by NSF award PHY-1301935.

3. References

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