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An approach to verification and validation of MHD codes for fusion applications

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HIGHLIGHTS

- Review of status of MHD codes for fusion applications.
- Selection of five benchmark problems.
- Guidance for verification and validation of MHD codes for fusion applications.

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ABSTRACT

We propose a new activity on verification and validation (V&V) of MHD codes presently employed by the fusion community as a predictive capability tool for liquid metal cooling applications, such as liquid metal blankets. The important steps in the development of MHD codes starting from the 1970s are outlined first and then basic MHD codes, which are currently in use by designers of liquid breeder blankets, are reviewed. A benchmark database of five problems has been proposed to cover a wide range of MHD flows from laminar fully developed to turbulent flows, which are of interest for fusion applications: (A) 2D fully developed laminar steady MHD flow, (B) 3D laminar, steady developing MHD flow in a non-uniform magnetic field, (C) quasi-two-dimensional MHD turbulent flow, (D) 3D turbulent MHD flow, and (E) MHD flow with heat transfer (buoyant convection). Finally, we introduce important details of the proposed activities, such as basic V&V rules and schedule. The main goal of the present paper is to help in establishing an efficient V&V framework and to initiate benchmarking among interested parties. The comparison results computed by the codes against analytical solutions and trusted experimental and numerical data as well as code-to-code comparisons will be presented and analyzed in companion paper/papers.

1. Introduction

This paper is a follow up of a talk given by the first author at the IEA Liquid Breeder Blanket (LBB) Workshop in Barcelona, Spain

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on September 21, 2013 about a new initiative aiming at verification and validation (V&V) of MHD codes, which have recently been used as a design/analysis tool for fusion applications, first of all, for liquid metal (LM) breeding blankets. There were about 40 attendees from the US, EU, Japan, China, Russia, India and Korea involved in liquid breeder activities in their countries, in particular in development of magnetohydrodynamic (MHD) codes. As a result of the subsequent round-table discussion, the participants had established a work group, agreed about basic V&V rules and the schedule and finally recommended a set of test cases for the upcoming benchmark activities.

The paper outlines major steps in development of MHD codes starting from the 1970s, summarizes the most important goals of the proposed test activities, introduces major MHD codes presently employed by the fusion community, selects five benchmark cases for laminar and turbulent MHD flows, and gives recommendations on how the testing of the codes could be organized among the participants. We also review earlier code benchmarking activities [1] for hydrodynamic flows. The main goal of the present paper is therefore to help in establishing an efficient framework for V&V of MHD codes for fusion applications. Results of the proposed testing will be reported in the next companion paper/papers when the test cases are completed by the performers. The expected duration of the proposed test studies is about one year from the moment when this paper is published.

This publication, as the title implies, is primarily concerned with verification and validation. These two terms are often confused especially when applied to computational fluid dynamics (CFD). Based on the AIAA glossary for CFD [2], *verification* is defined as the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. In other words, verification can be described as "solving the equations right". *Validation* is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Validation has also been described as "solving the right equations". *CFD benchmarking* is the key approach used to verify and validate a code, which includes the comparison of numerical data produced by a code with reference values, which are commonly accepted by the CFD community. Code benchmarking can include comparisons with experimental data or testing against trusted numerical data or analytical solutions.

The main objectives of the proposed activities on V&V of MHD codes for fusion applications, as agreed among the participants of the LBB workshop in Barcelona, are the following:

- To help the code developers to improve their computational tools via code-to-code comparisons as well as benchmarking against available analytical solutions and existing and near-future experimental data and also against trusted numerical data.
- To establish a benchmark database.
- To share information about recent code development.
- To attract more attention in the fusion community to problems and difficulties in developing fusion-relevant MHD codes as a tool for LM blanket design and analysis.
- To educate current and potential users about code capabilities and limitations to encourage "critical thinking" and "thoughtful approach" when applying MHD codes to fusion problems.
- To start developing a policy on the control of computational quality, in particular to provide reviewers of fusion journals with a set of criteria by which the reviewers can judge the quality of publications in the area of computational MHD (CMHD).

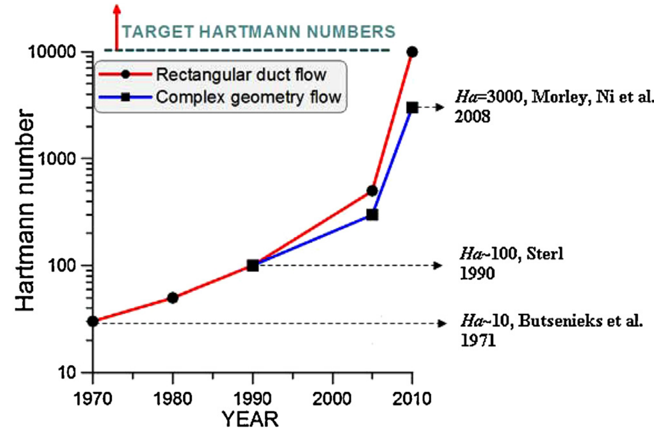

Fig. 1. Progress in MHD computations in terms of the Hartmann number.

2. MHD modeling background

At present, there is a critical demand in the fusion community for effective MHD codes that could be (i) used for LBB design and analysis and (ii) implemented in integrated modeling tools to address multiple physical effects in blanket flows. Unfortunately, only a few large MHD codes are presently available for blanket applications, which are, in fact, less mature than ordinary CFD codes. Their applicability to the full-scale fusion problems is still limited by the magnetic field strength, flow velocity and geometrical complexity. These limitations can be illustrated with a simple diagram (Fig. 1), which shows the progress in the MHD code development in terms of the dimensionless magnetic field strength, *Hartmann number*, defined as $Ha = B_0 L\sqrt{\sigma/\nu\rho}$, where B_0 is the strength of the applied magnetic field, L is the cross-sectional dimension of the flow-carrying duct, σ is the electrical conductivity of the working fluid, and ν and ρ are the fluid kinematic viscosity and density. For flows in a rectangular duct, which is a key geometrical element of any LM blanket design, the duct half-width b in the direction of the applied magnetic field is typically used as the length-scale: $L = b$. Hartmann number squared is also interpreted as the ratio between MHD and viscous forces. MHD computations were pioneered in the 1970s but at that time were limited to Hartmann numbers of a few tens [3]. The computations progressed quickly over the next three decades reaching Hartmann numbers on the order of hundreds in the late 1980s (e.g., [4]) and a few thousands recently [5]. Significant acceleration in MHD computations can be seen at around 2005 due to development of a new consistent and conservative scheme [6]. However, the progress has been different between simple geometry flows (*e.g.* in a straight rectangular duct) and more complex flows in blanket-relevant geometries, such as manifolds, contractions, expansions, bends as also shown in Fig. 1. Although high values of the flow parameters can be achieved in present computations for simple flow geometries (e.g. $Ha \sim 10^4$ in the case of fully developed flows in a duct), computations for complex geometries are still limited to significantly lower values.

Typically, MHD flows in a LM blanket are coupled with heat and mass transfer and demonstrate various unsteady features, including instabilities and MHD turbulence. In addition to the Hartmann number, other important relevant parameters are: the *Grashof number* that characterizes buoyancy forces relative to viscous forces $Gr = g\beta\Delta TL^3/\nu^2$ (β is the volumetric thermal expansion coefficient, g is acceleration of gravity, and ΔT is a characteristic temperature difference in the fluid), and the hydrodynamic *Reynolds number* (ratio of inertia to viscous forces) defined through the mean bulk velocity U_m as $Re = U_m L/\nu$. Present computations for 3D MHD flows with buoyancy forces are limited to $Gr \sim 10^8$, while the target value for blanket applications is $Gr \sim 10^{12}$ [7]. The Hartmann and the