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Synergy of experiments and computer simulations in research of turbulent convection

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Abstract

We discuss the potential and limitations of current experimental and simulation techniques and their synergy in the research of turbulent convection. Examples from our recent experience are presented where complementing of experimental and simulation approaches has not only provided precious information, but has also revealed some unexpected phenomena which could have remained hidden if the problem was investigated only experimentally or only by simulations. Among examples considered are the two paradigms of turbulent flows and heat transfer, and a challenging MHD problem: 1. Thermal convection over horizontal surfaces in a broad range of conditions including extreme ones, covering experiments for $\mathrm{Ra} = 10^8$–10^9, DNS for $\mathrm{Ra} = 10^5$–10^8, LES for 10^6–10^9 and VLES/T-RANS for $\mathrm{Ra} = 10^6$–2×10^{16}; 2. Experimental, RANS and LES studies of flow structure and heat transfer in single and multiple impinging jets at higher Re numbers; 3. Computer-simulation of a model of fluid-magnetic dynamo, in association with experiments in Riga (Latvia) and Dresden (Germany).

Keywords: Turbulent convection; Experiments; Computer simulations; Synergy

1. Introduction

Benefits of synergy of experiments, theories, analytical, computational and other research methods, have long been recognized in science and all methods have been practiced in parallel, complementing each other. Yet, scientists tend to specialize in one or other research method or field, remaining predominantly either experimentalists, theoreticians, or numericists (computationalists). The research interaction often remains within relatively closed communities, results are published in specialized experimental, theoretical or computational journals, and communications practiced at specialized conferences.

A particular gap emerged with the advent and rapid development of computer simulations. These have been adored and worshiped by some to the point of exaltation ('experiments will become obsolete and wind tunnels will be turned into computer output storages'), while mistrusted and undermined by others, sometimes to the point of ridicule ('garbage in, garbage out'). As we all know, wind tunnels were not converted into storages. Not because the computer printouts disappeared and gave way to electronic media and graphics, but because experimental research has been steadily gaining in importance, inspired and promoted—paradoxically or not—also by computer simulations. The development of simulation techniques requires (next to theory) reliable data for validating, verifying and calibrating numerical schemes, methods, mathematical models, and such data in most cases can be provided only by measurements. A large number of experiments have been dedicated specifically to provide reference data for validating models and methods used in simulations. The reverse is also true: most simulations, especially when promoting new methods or models, focus on problems already investigated experimentally, thus replicating experiments (often for its own sake to verify the theory or model and to provide a proof of accuracy) but producing more data and new information, some of which may be inaccessible

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to experiments. It is this kind of mutual feedback between experimental and simulation research that has shown especially great potential for synergy.

The progress in laser and spectroscopic diagnostics (LDA, PIV, PTF, LIF, CARS, etc.), in holography, MRI and other new techniques, have opened new prospects for non-intrusive measurements of *almost* all relevant properties of flows, heat and mass transfer in non-reacting and reacting (combusting) single and multiphase flows. New wind tunnels have been built and more are planned, especially to achieve extreme *Re* and *Ra* numbers. In parallel, the techniques of computer simulations have made enormous progress making it possible, at least in a limited class of problems, to acquire *all* information required or imagined. The potential of computer simulations to provide full time-dependent three-dimensional fields has also prompted and stimulated spectacular progress in computer visualization and animation which make it possible to get a full insight into miniscule and subtle details of flow structures and their time evolution and dynamics in three-dimensional space.

Developing of *research methods* (experimental techniques and instruments, numerical schemes and models, specific theories, etc.) requires usually life dedication leaving little time and motivation for excursions into other areas and radical changes of research specialization. In contrast, research aimed at *acquiring new knowledge* and gaining deeper insight into physics of various phenomena can greatly benefit from combined and simultaneous experiments and computer simulations (with, of course, a blend of theory) in overcoming barriers and limitations of each, and expanding the frontiers of our cognition. A number of research groups are pursuing such a dual track.

The potential for synergy is broad and versatile; it is often unpredictable and sometimes comes as a surprise. In most cases one follows common sense by recognizing limitations and potentials of each method and compensates for deficiencies by using other methods. It is beyond the scope of this article to try to postulate rules and recommendations. Instead we present here some examples from our experience where complementing of experimental and simulation approaches has not only provided precious information, but has also revealed some unexpected phenomena which could have remained hidden if the problem was investigated only experimentally or only by simulations. Among examples considered are the two paradigms of turbulent flows and heat transfer, and a challenging MHD problem:

- Thermal convection over horizontal surfaces in a broad range of conditions including extreme ones: experiments for $Ra = 10^8$–10^9, DNS for $Ra = 10^5$–10^8, LES for 10^6–10^9 and VLES/T-RANS for $Ra = 10^6$–2×10^{16}.
- Impinging flows and heat transfer at higher *Re* numbers: experiments, RANS and LES of a single round jet for $Re = 20\,000$ $H/D = 2$–6, and experiments and RANS of multiple jets in in-line and hexagonal arrangements.
- Computer-simulation of a model of fluid-magnetic dynamo, in association with experiments in Riga (Latvia) and Dresden (Germany).

2. Rayleigh–Bénard convection: Some old and new challenges

Rayleigh–Bénard (R–B) convection has long served as a paradigm of thermal convection. Despite its geometric simplicity – fluid trapped between two horizontal walls heated from below and cooled from above – at sufficiently high Rayleigh number $Ra = g\beta\Delta TL^3/\alpha\nu$ contains most events, structures and features pertinent to real large-scale phenomena in environmental, terrestrial and in many technological systems. Here β is the thermal expansion coefficient, α is temperature diffusivity, ν is kinematic viscosity, ΔT the imposed temperature difference and L the characteristic length scale.

Research in R–B convection has stirred much controversy. At the core is the $Nu \propto Ra^n$ correlation, where $Nu = hL/k$ is Nusselt number (where h is the heat transfer coefficient and k the fluid conductivity), but the scaling controversy reflects the general disagreement about the underlying physics and heat transfer mechanism. The interest, especially at high *Ra* ($>10^{12}$) is motivated not only by scientific curiosity, but also by the importance of the R–B phenomenon in understanding thermal convection in the atmosphere, oceans, earth mantle, and in engineering equipment.

The classic correlation $Nu = Ra^{1/3}$ implies no communication between the two horizontal walls (hence no effect of their distance) and the heat flux is assumed to be governed by the processes confined within the wall boundary layers. This implies that the plumes generated on one of the walls never reach the other wall. While this theory may sound reasonable at low *Ra* numbers, it seems unlikely at high *Ra* since persistent plumes (that may break into thermals or puffs) propelling and stretching from one to another wall have been observed experimentally as well as in numerical simulations. Wall communication involves a different heat transfer scenario, as argued by several researchers (e.g. Siggia, 1994) resulting in a different *Ra* exponent. Most evidence seems to support 2/7 scaling ("hard" regime) observed by the Chicago group (Castaigne et al., 1989) for $Ra > 4 \times 10^7$ in their experiment with helium. However, other experiments using water report the 1/3 power law for $Ra > 10^9$ with a smaller exponent for low *Ra* numbers (Siggia, 1994, p. 151). While the small difference in the *Ra* exponent may not be a reliable indicator, reports on other parameters, which provide better indication of the change in the regime, are also inconsistent.

Even larger controversy surrounds the very high *Ra* numbers, roughly beyond 10^{12}, for which the Grenoble group (Chavanne et al., 1997; Chavanne et al., 2001; Roche et al., 2001) observed another, "ultra hard" regime characterized by an increase in the *Ra* exponent to about 0.38 to 0.39 (for $10^{11} < Ra < 2 \times 10^{14}$), indicating a trend towards