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The dynamo effect/L'effet dynamo

Interplay between experimental and numerical approaches in the fluid dynamo problem

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Abstract

After years of purely analytical and numerical investigations, the dynamo fluid problem has advanced to a phase of experimental study. We present an outline of the numerical steps that have accompanied the Von Kármán Sodium (VKS) experiment at Cadarache for the past ten years. We show how various numerical studies contributed progressively to the optimization of the experimental facility. The recent success of the VKS2 experiment of September 2006 in achieving dynamo action has prompted an extension of the numerical code. Modeling of the electromotive force induced in the volume of the impellers shows that an axial dipole is excited, as observed in the experiment. We infer from these results that the observed value of the critical magnetic Reynolds number may be linked to the soft iron of the impellers and not to turbulence which occurs for any choice of materials. We conclude with proposals for further lines of numerical development. ***To cite this article: J. Léorat, C. Nore, C. R. Physique 9 (2008).***

Résumé

Couplage entre approches numériques et expérimentales dans le problème de la dynamo fluide. Après avoir connu une longue période d'études purement analytiques ou numériques, le problème de la dynamo fluide est entré dans une phase expérimentale depuis quelques années. Nous proposons un résumé des étapes numériques qui ont accompagné la réalisation de l'expérience Von Kármán Sodium (VKS) à Cadarache. Nous montrons comment des études numériques très diverses et successives ont contribué à l'optimisation progressive du montage expérimental. Enfin, le succès de l'expérience VKS2 de septembre 2006 a suscité une extension du programme numérique avec une modélisation de l'induction dans le volume des turbines. Les résultats permettent de conclure que ce n'est pas la turbulence qui contraint le nombre de Reynolds magnétique critique à la valeur observée, mais le fer doux des turbines. Des perspectives de développement numérique sont proposées en conclusion. ***Pour citer cet article : J. Léorat, C. Nore, C. R. Physique 9 (2008).***

Keywords: Fluid dynamo; Kinematic code; Magnetic boundary conditions

Mots-clés : Dynamo fluide ; Simulations cinématiques ; Conditions aux limites magnétiques

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En nous basant sur l'exemple de l'expérience Von Kármán Sodium (VKS) de Cadarache, nous nous proposons de montrer la complémentarité des approches expérimentales et numériques dans le traitement du problème de la dynamo fluide. Alors que l'entraînement du fluide par des turbines contra-rotatives est utilisé dans trois expériences MHD dans le monde, seule l'expérience VKS2 de septembre 2006 a produit l'effet dynamo recherché. Les simulations numériques peuvent-elles aider à la compréhension de ce résultat alors que l'écoulement a un nombre de Reynolds proche de 10^7 inaccessible au calcul direct ?

Les étapes successives de l'accompagnement numérique du projet expérimental sont décrites de façon chronologique. La première était basée sur des codes non linéaires périodiques dans les trois directions cartésiennes, avec un forçage volumique de type Taylor–Green. Bien que ces codes soient toujours utilisés pour traiter des effets non linéaires en MHD, les flots ainsi engendrés semblent trop différents de ceux mesurés pour prédire des nombres de Reynolds magnétiques critiques (Rm_c) réalistes. Les étapes suivantes exploitent donc des codes de dynamo cinématique en géometrie cylindrique, utilisant un champ de vitesse moyen mesuré dans une expérience en eau. La deuxième étape fait appel à un code axialement périodique, qui permet de comparer l'efficacité de différents types de turbines et de montrer l'intérêt d'une enveloppe latérale conductrice pour diminuer le nombre de Reynolds magnétique critique. Ces acquis sont confirmés dans l'étape suivante qui aborde enfin la géométrie du cylindre fini avec deux codes indépendants (méthode intégrale d'une part, et éléments finis d'autre part). Il devient possible de montrer l'influence négative du fluide conducteur au-delà des turbines et de traiter les domaines de différentes conductivités (sodium, acier et cuivre). Les prédictions cinématiques sur la croissance du mode $m = 1$ n'ont pas été vérifiées dans l'expérience dynamo de septembre 2006, qui a montré que l'écoulement moyen devait être complété par des composantes non axisymétriques. Nous nous sommes placés dans le cadre de la modélisation de l'induction moyenne par un terme d'effet alpha restreint au volume des turbines. On retrouve alors la croissance du mode magnétique $m = 0$ associé à un coefficient alpha réaliste pour le Rm_c observé, plus faible dans l'hypothèse d'une perméabilité magnétique infinie (turbines en fer doux) que pour une interface avec le vide (turbines en acier). En conclusion, le rôle du fer doux semble prépondérant dans le succès de l'expérience analysée alors que la turbulence, si elle intervient, aurait plutôt un rôle négatif. La poursuite de la comparaison entre expériences et simulations devrait être instructive. Les perspectives numériques sont esquissées, par exemple, développement d'un algorithme autorisant des domaines de différentes perméabilités ou inclusion d'un forçage en vue d'examiner le régime de saturation non linéaire.

1. Introduction

Beginning in the 1950s, the numerical approach to the generation of magnetic fields from velocity fields, i.e. *the dynamo action*, appears as one of the first civilian applications in the history of computer science. Dynamo action is possible only when the following necessary condition is satisfied: the control parameter, the magnetic Reynolds number defined as $Rm = UL/\eta$ with U, L the characteristic speed and length respectively and η the magnetic diffusivity, must exceed a threshold which depends on the kinetic Reynolds number $Re = UL/\nu$ with ν the kinematic viscosity. The ratio $Rm/Re \equiv Pm$ is the magnetic Prandtl number which is about 10^{-5} for liquid metals. In the present paper, we investigate the impact of the numerical contributions for about 10 years on an experimental facility, the von Kármán Sodium (VKS) experiment, designed to realize dynamo action in the laboratory.

For more than 30 years, most of the numerical studies concerning dynamo action were aimed at demonstrating the occurrence of the phenomenon using academic flows, with no relation to their practical realization. The question of experimental fluid dynamos became more practical with the development of fast breeder reactors using large scale flows of liquid sodium (such as BN600 in the Soviet Union and Superphenix in France). Such facilities at that time held the record for largest magnetic Reynolds numbers, below 20. We note here that these industrial installations were developed without computational investigation on the possible occurrence of dynamo action. For design studies of a future generation of breeder reactors, the situation will surely change to take advantage of numerical codes which have been written for studying experimental fluid dynamos.

Since there is no sufficient condition for dynamo action, the only way to know if a given flow will lead to dynamo action is to try it. This approach is currently used, for example, by D. Lathrop [1], who is able to explore fundamental features of large Rm flows and test different driving parameters using a versatile spherical container (diameter 60 cm). This configuration avoids difficult and lengthy numerical simulations. In other cases, to reduce the experimental expenses, numerical experiments may be used to select and optimize the final configuration. This alternative approach has been followed by the three successful dynamo experiments [2–4]. Numerical experiments may also point out that achievement of the critical magnetic Reynolds number in a given experimental facility is problematic (due to turbulence, say, [5]) and thus lead to a redefinition of realistic scientific objectives.

To summarize, the main challenges for experimental dynamo action using the best conducting fluid, liquid sodium ($Pm = 10^{-5}$), may be represented by two constraints on the basic flow parameters:

– $Rm > 10 \Rightarrow UL > 1\ \mathrm{m^2\,s^{-1}}$: experimental challenge,
– $Re > 10^6$: numerical challenge.

The first two dynamo experiments were inspired by two analytical kinematic dynamos [6,7], which led to constraints on the flow by interior walls (using pipe flows, with low turbulence intensity). On the other hand, the aim of the VKS experiment was to reach dynamo action without internal walls. Its starting point is an hydrodynamic experiment, using counter-rotating coaxial disks in a cylindrical container [8]. This design is now also known as the "French washing machine". To benefit from the efficiency of inertial driving, the smooth disks are replaced by impellers with blades of height of about 10% of the container length. While smooth walls may be used in direct numerical simulations at Reynolds numbers below 1000 [9], the blade driving configuration is numerically out of reach and leads to a turbulent flow including nonaxisymmetric small scales. Various approximations or models of the resulting flow have been considered and are recalled below in chronological order. We try here to draw attention to the main steps of this story only and the interested reader may find more details on the results in the references.

2. First step: periodic Cartesian geometry and nonlinear codes

Since the VKS driving configuration has been chosen on hydrodynamic grounds, the first question to settle concerns the possibility of dynamo action of the resulting flow. The simplest way to numerically answer such a question appears to be to use periodic boundary conditions in the three Cartesian directions. Periodic magnetohydrodynamic (MHD) codes based on pseudo-spectral methods involving fast Fourier transforms are known to be highly efficient. The classical Taylor–Green (TG) vortex is a convenient model of the driving acceleration field which presents with the VK flow a similarity in overall geometry: a shear layer between two counter-rotating eddies. The TG vortex, however, is periodic with free-slip boundaries while the VK flow is contained inside a tank and the TG forcing acts in the whole fluid volume while the impellers act in a relatively small volume. The TG field presents various symmetry properties which can be implemented in a TG symmetric code in order to save computer resources [10]. In these simulations [11], *Rm* and *Re* are based on the *root-mean-square* velocity and the integral scale. Two different studies have been conducted in parallel using a TG symmetric code and a standard periodic code in which no symmetries are implemented [11]. Three types of forcing in the Navier–Stokes problem have been tested [12]: constant velocity, constant force and constant injection power. The constant velocity forcing is usually used in the MHD runs for its simplicity [11,13]. The general periodic code leads to a nonsymmetric *slab* magnetic field displayed in Fig. 1(a) at the scale of the total box $[0; 2\pi]^3$. With the TG symmetric code, a forcing at a smaller scale than the periodic length is seen to reduce the critical magnetic Reynolds number: Rm_c varies from 250 to 20 with decreasing forcing scale. A typical temporally averaged magnetic field is shown in Fig. 1(b): magnetic structures are elongated along the vertical axis of the impermeable box $[0; \pi]^3$ and are directed at the center while the small-scale vorticity field is wrapped around.

These early nonlinear studies have been progressively extended, using standard periodic codes but different types of forcing [13–15]. They showed the existence of two windows of kinematic dynamo action, one low branch around $20 \leqslant Rm \leqslant 50$ and one high branch for $Rm > 150$. The low branch is associated with a large scale magnetic field extended in the entire box $[0; 2\pi]^3$, reminiscent of the *slab* mode [11], while the high branch confined to the impermeable box $[0; \pi]^3$ could be related to the VK unstable branch. The search for periodic dynamos is encouraging for the VKS configuration, but has to be confirmed by more realistic solutions. Note, however, that this sub-domain of the field of numerical dynamos is still very active, as shown recently by the discovery of a subcritical dynamo bifurcation [15] for the two types of forcing, constant velocity and constant force.

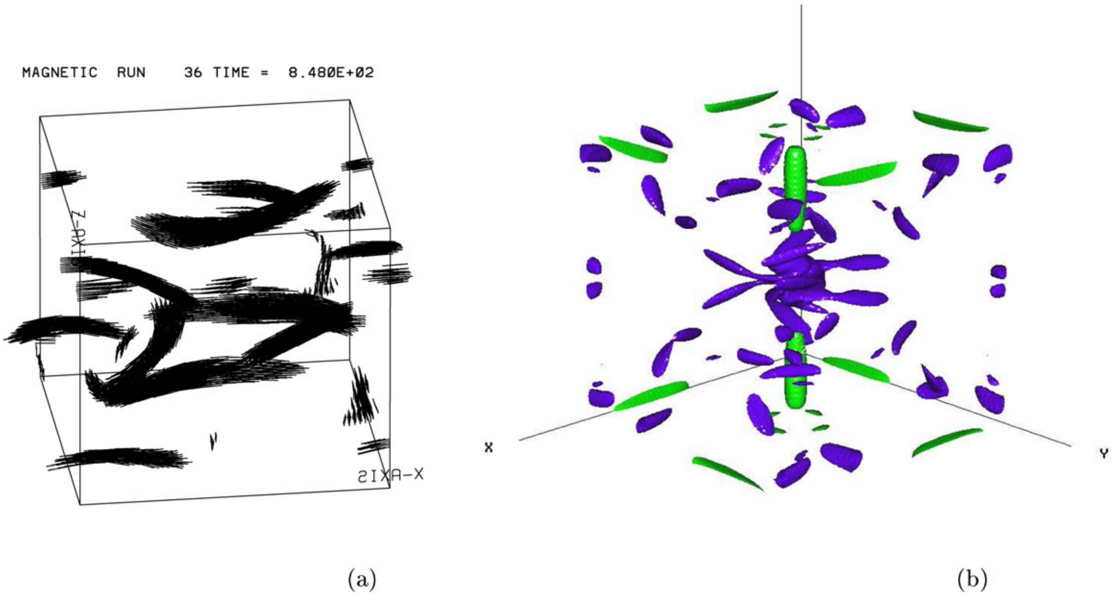

Fig. 1. Nonlinear Taylor–Green (TG) dynamo [11]: (a) Magnetic field vectors for the TG periodic code in the total box $[0; 2\pi]^3$ for $Rm = 41 > Rm_c \simeq 10$ and $Re = 10.3$. Slab geometry. (b) Isosurfaces of $\overline{B^2} = 10\%$ max (grey) and $\omega^2(t = 256) = 20\%$ max (black) for the TG symmetric code in the impermeable box $[0; \pi]^3$ for $Rm = 44 > Rm_c \simeq 40$ and $Re = 25$.

3. Second step: axially periodic cylindrical code

In order to evaluate the critical magnetic Reynolds number of a given flow, the only known alternative to the computational approach is to measure the decay rate of a magnetic external perturbation in the flow and extrapolate the critical magnetic Reynolds number Rm_c for which the rate vanishes. This empirical method may be effectively used only if the flow can reach a Rm close enough to the critical one. The scaling and initial design of VKS were based on induction results obtained with an existing gallium experiment [16]. It appeared that the magnetic Reynolds number of the gallium flow was too subcritical to learn anything about dynamo action in the VKS experiment under construction in CEA-Cadarache. Rather a numerical approach was advisable, providing the opportunity to reduce the critical magnetic Reynolds number by optimizing the driving configuration.

Years of numerical simulations have shown that the dynamo properties of a flow strongly depend on the precise flow geometry, and hence, as recalled above, the Rm_c obtained using bulk forcing with periodic boundary conditions could not be adapted for the VKS device. As a nonlinear MHD code able to describe such an experiment was not available at that time, a kinematic dynamo code in a cylinder with axially periodic conditions was first used [17]. The flow velocity field was obtained in a half-scale water experiment using laser Doppler velocimetry (and now PIV). An important feature of this procedure is that the flow is averaged in time and space, meaning that small scales, nonaxisymmetric components and time fluctuations are filtered out. To compute periodic solutions of the induction equation, the flow also has to be periodic. The original velocity field is symmetrized with respect to the center of a turbine. The resulting axial length (i.e. the double of the experimental one) is taken as the fundamental period of the solution. The azimuthal component of the flow thus appears to have a period twice that of the poloidal recirculation. This study [18,19] showed that the growing magnetic field is a stationary $m = 1$ mode (with m the azimuthal wavenumber in cylindrical coordinates) dominated by an horizontal dipole and two vertical structures aligned with the cylinder axis. It also demonstrated how the critical magnetic Reynolds number may be reduced by varying the ratio of the poloidal to the toroidal flow components and also by adding a lateral conducting static envelope. This led to an impeller selection procedure, by alternating water experiments and dynamo simulations. However, the Rm which could be achieved in the VKS1 experiment could not reach the threshold determined by the kinematic computations. It was thus decided to double the electrical driving power, from 150 kW to 300 kW, with a new set-up including features learned from the axially periodic results and also from new outcomes to be described below.

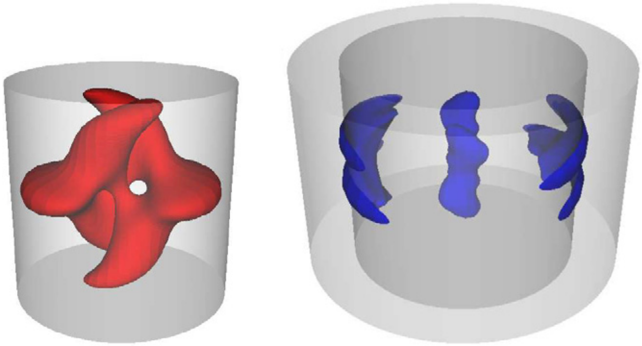

Fig. 2. Kinematic dynamo in a finite cylinder, $m = 1$ mode. Isovalue of 25% of the maximum energy of the growing magnetic field for (a) the MND [22] flow at $Rm = 65 > Rm_c = 63.5$ and vacuum boundary conditions [26]; (b) the VK flow at $Rm = 40 > Rm_c = 38$, a lateral width $w = 0.4$ of static copper (jump of conductivity of 5) and vacuum boundary conditions [26].

4. Third step: finite cylinder and kinematic code

Being aware of the importance of the magnetic boundary conditions (i.e. continuity of the internal magnetic field with the external vacuum solution), we have developed a new nonlinear MHD code adapted to dynamo problems with axisymmetric interfaces [20]. It is called SFEMaNS for Spectral Finite Element code for Maxwell and Navier–Stokes equations. Before SFEMaNS became operational, a kinematic dynamo code for a finite cylinder based on integral methods became available [21], where, due to methodological reasons, no conductivity jump between the vessel and the fluid was considered. Numerical simulations on VKS2-like set-ups (i.e. finite length and vacuum interface) have been carried out in [21] to evaluate the influence of the thickness of the vessel containing the sodium. First, the decrease of the critical magnetic Reynolds number when the thickness of the side walls of the vessel is increased was confirmed for the finite length cylinder. The surprise came from the disastrous impact on the critical magnetic Reynolds number of an increase of the flow thickness behind the bottom and top impellers [21]. In the periodic code [19], such layers were not taken into account since it requires an increase in the number of axial modes in a zone where the periodic magnetic boundary conditions are known to be artificial.

A small decrease in Rm_c is crucial from the experimental point of view, since the power needed in the experiment scales like $\mathcal{O}(Rm^3)$. These results have led us to redo the computations with a more realistic copper vessel, with conductivity ratio $\sigma_{\text{copper}}/\sigma_{\text{sodium}} \simeq 5$, using SFEMaNS which can account for discontinuous conductivities. We first examined the kinematic dynamo with an analytical flow [22]. With vacuum boundary conditions, the growing magnetic field with $m = 1$ is similar to the one found in [19,21] (see Fig. 2(a)). We have shown [23] that adding a conducting envelope around the vessel lowers Rm_c and that increasing the envelope conductivity from 1 (sodium) to 5 (copper) significantly amplifies this effect. We have also verified that Rm_c increases with the thickness of the top and bottom lids and that this effect is also amplified by the conductivity jump. Using the same analytical flow [22], a recent study [24] has confirmed that high magnetic permeability boundary conditions decrease Rm_c [25]. Complete confirmation of all of these meaningful features was then achieved using the axisymmetric flow obtained from the water experiment in CEA-Saclay [19] (see Fig. 2(b)). We have also investigated more realistic configurations including the copper external wall, the stainless impellers, the static sodium lateral layer and the flow behind the impellers. Any configuration without motion behind the impellers leads to $Rm_c \simeq 50$, whereas the case with a pure azimuthal motion [26] behind the lids multiplies the threshold by 3!

5. Fourth step: alpha-VKS

In order to decouple the magnetic influence of the flow behind the impellers from the central bulk flow, the stainless steel formerly used in the impellers of the VKS1 facility could be replaced by soft iron in the VKS2 new facility. This was indeed the case for the first run with the new design in September 2006, where an annulus was also added in the equatorial plane to reduce the temporal oscillations of the median shear layer. An account of the experimental success is given in [4] and the present special issue of C. R. Physique. One can thus ask: "Can the numerical approach explain the VKS2 success in September 2006?".

The experimentally observed domination of the azimuthal $m = 0$ mode in the equatorial plane and the Cowling anti-dynamo theorem prove straightforwardly that the axisymmetric flow used in all the previous kinematic computations was too crude an approximation. Moreover, the observed critical magnetic Reynolds number of about 32, much smaller that the previously computed Rm_c, confirms the need to re-examine the setting of the simulations. After this successful experiment based on a new design, two new questions at least need to be tackled numerically: how to deal with the nonaxisymmetric modes? What is the role of soft iron?

We have thus extended the former kinematic studies including realistic geometry and boundary conditions, by modeling the inductive action of the small scale flow generated between the blades of the impellers as suggested by [27]. This flow has two basic features which bring some support to the modeling: (i) the small blade size leads to an effective magnetic Reynolds number of order one. Thus in a given external mean field the induced field would remain small which is compatible with the first order smoothing approximation; (ii) Although the Reynolds number remains high (with the magnetic Prandtl number $Pm = 10^{-5}$), the channel between the blades constrains the flow, which resembles a steady helical flow (screw motion around a radial axis) with a positive helicity. The counter-rotation configuration with $\Omega_{\text{bot}} = \Omega = -\Omega_{\text{top}}$ is invariant by rotation of π about any horizontal axis [9], therefore the two impellers produce the same helicity, such that the product of the rotation angular velocity Ω with the helicity produced by the blade screw motion is always positive. Note that improvement of this crude model will need large numerical simulations such as the ones performed for turbo-machines, with attention to the peculiar impeller geometry (including blade curvature).

As is currently done in kinematic dynamo problems, the azimuthally averaged electromotive force induced by this small scale flow on the large scale mean magnetic field is represented by an alpha-effect tensor, which is represented by 9 coefficients depending on r and z. Phenomenological arguments help to reduce the parameter space to a single coefficient (denoted α below). This alpha-effect generates an azimuthal current from an azimuthal mean field, which means that it converts toroidal components into poloidal ones, a particularly welcome operation! Since the alpha coefficient is strongly connected to the impeller volume, we choose it to be constant within a small layer (about 10% of the total flow volume) and zero outside. As in former simulations, note that the different azimuthal modes m are decoupled since all the coefficients of the induction equation are still axisymmetric.

In order to match the experiments, two types of magnetic boundary conditions are compared: for steel impellers, vacuum is assumed beyond the impellers, while for soft iron impellers, we take the limit of infinite magnetic permeability such that the tangential magnetic field (i.e. azimuthal and radial components) vanishes at the surface of the impellers. In the parameter plane (α, Rm), dynamo action occurs beyond a critical curve for each magnetic boundary condition (not shown here [28]). As expected from Cowling's theorem, the $m = 0$ mode may be excited only if α differs from zero (see Fig. 3). It must also have the appropriate sign, in agreement with the phenomenological analysis of the alpha-effect (alpha is negative for positive helicity). Long experience with alpha-effect modeling has shown the decrease of Rm_c for the $m = 0$ mode, when the amplitude of $|\alpha|$ increases. This is confirmed here, with a power law for the two critical curves with different boundary conditions like $Rm|\alpha|^{0.67} = const$.

The most striking result appears to be the influence of soft iron, which is indeed able to reduce the critical magnetic Reynolds number to 32 for the axisymmetric magnetic field with a sensible value of α. If the same value of α is retained for the steel impellers (same blade geometry in both cases), the predicted critical Rm turns out to be close to 45, which has not been observed. We shall not pursue here the comparisons between numerical and experimental results, since the axisymmetric flow used in the present simulations (see [28]) is not exactly the one driven by the actual configurations. With our present knowledge of the VKS2 experimental results and numerical simulations, we conclude that it is not turbulence which is the main actor in dynamo action observed at $Rm_c = 32$, but the coexistence of three circumstances: the high permeability of the impellers, the induction effect in the axisymmetric flow between them and the helicity effect within the impeller blades.

6. Conclusion

All the steps of our numerical path described above, including the last one, illustrate clearly the unending interplay between MHD experiments and simulations, a long-standing standard process in hydrodynamics. First, different types of kinematic dynamo codes have contributed to the optimization of the VKS experiment in the following items: – se-

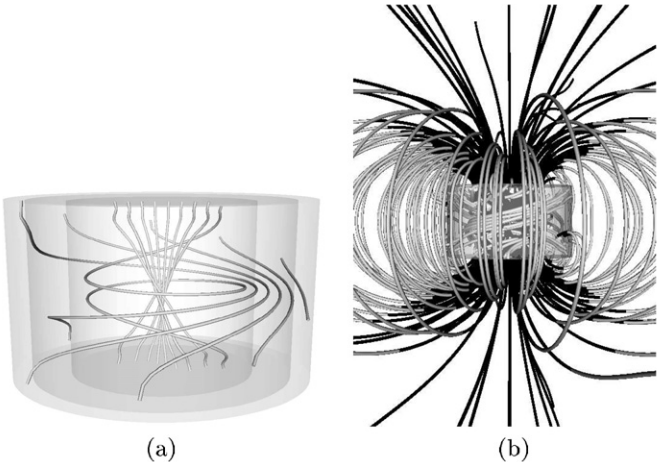

Fig. 3. Kinematic dynamo in a finite cylinder, axisymmetric mode. Magnetic field lines of the $m = 0$ growing magnetic field for $Rm = 32$, $|\alpha| = 2.2 > |\alpha_c| = 2.1$ and ferromagnetic boundary conditions: (a) inside the three coaxial cylinders, (b) outside the container (black (white) for positive (negative) B_z component). More details in [28].

lection of impellers with efficient poloidal/toroidal ratio – positive effect of a conductive envelope on the curved lateral wall, including materials with different conductivities (liquid sodium, steel, copper) – negative effect of a conducting flow behind the impellers. Second, the VKS experimental results have confirmed the important role of magnetic boundary conditions and have helped to develop more relevant kinematic or nonlinear codes. To describe the VKS2 experiment, we have taken the limit of infinite relative permeability μ_r, while the soft iron impellers have $\mu_r \simeq 200$. This is a rather crude description, which avoids dealing with the magnetic coupling between the flow and the impellers. A future study will investigate the simulation of dynamo problems including conductive domains with different permeabilities. This new possibility is now being considered as an extension of our finite element code SFEMaNS, although it is more involved than the present treatment of domains with different conductivities, as the magnetic field becomes discontinuous at an interface where a permeability jump is allowed. This seems to be an interesting problem, although it may be considered to range beyond the proper dynamo problem, where imposing magnetic circuits may look artificial. Note also that apart from the important role played by the high magnetic permeability domain, the VKS configuration departs strongly from natural dynamos: since each impeller acts as a brake against the other, the turbulence level and dissipated power are bound to stay relatively high. The next generation of fluid dynamo experiments will hopefully adopt driving configurations closer to natural dynamos. Large scale forcing would presumably allow us to reach larger magnetic Reynolds numbers, but to remain feasible, critical magnetic Reynolds numbers below 100 must be found. Such a step is strongly needed, not just to obtain another proof of dynamo action but also to support the design of a MHD wind tunnel. Such a facility is essential for validating MHD turbulence models being developed for fundamentals aspects as well as for astrophysical applications.

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