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Thermal convection in a toroidal duct of a liquid metal blanket. Part I. Effect of poloidal magnetic field

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HIGHLIGHTS

- 2D convection flow develops with internal heating and strong axial magnetic field.
- Poloidal magnetic field suppresses turbulence at high Hartmann number.
- Flow structure is dominated by large-scale counter-rotation vortices.
- Effective heat transfer is maintained by surviving convection structures.

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ABSTRACT

We explore the effect of poloidal magnetic field on the thermal convection flow in a toroidal duct of a generic liquid metal blanket. Non-uniform strong heating (the Grashof number up to 10^{11}) arising from the interaction of high-speed neutrons with the liquid breeder, and strong magnetic field (the Hartmann number up to 10^4) corresponding to the realistic reactor conditions are considered. The study continues our earlier work [1], where the problem was solved for a purely toroidal magnetic field and the convection was found to result in two-dimensional turbulence and strong mixing within the duct. Here, we find that the poloidal component of the magnetic field suppresses turbulence, reduces the flow's kinetic energy and high-amplitude temperature fluctuations, and, at high values of Hartmann number, leads to a steady-state flow. At the same time, the intense mixing by the surviving convection structures remains able to maintain effective heat transfer between the liquid metal and the walls.

1. Introduction

The use of lithium-containing liquid metals (pure Li or LiPb alloy) as a cooling, shielding, and breeding material in fusion reactor blankets is a promising concept. Development of such blankets is, however, far from complete and faces serious challenges [2]. Two factors are particularly important to understand as they determine the flow and heat transfer in the liquid metal. One is the internal heating caused by the high-energy neutrons generated in the fusion reaction and captured by the liquid metal. The conversion of the neutrons' kinetic energy into heat leads to very intensive (tens of MW/m^3 near the wall facing the reaction chamber) steady internal heating and implies strong potential for thermal convection. The second factor is the exposure of the blanket to a very strong (up to 10–12 T) magnetic field.

Traditionally, the studies of liquid metal flow within the blanket were focused on the magnetohydrodynamic (MHD) effects, in particular, on the prediction and ways of reduction of MHD pressure drop. Recently, more concerns have been given to the effects of thermal convection. Laboratory experiments [3,4] and computations [1,5–12] carried out at various but, generally, moderately high values of Hartmann and Grashof numbers have addressed this issue. Although the typical parameters corresponding to the conditions of a real fusion reactor cannot yet be attained in such studies, the results provide convincing indications that the thermal buoyancy-driven convection profoundly affects the flow structures and transport properties and may lead to safety and efficiency problems in blanket performance. In many configurations, in particular in flows through vertical [3,4,7,10] and horizontal [12] ducts and in boxes with conducting walls [9], the convection leads to large-amplitude low-frequency fluctuations of temperature (the so-called 'anomalous fluctuations') or to formation of hot and cold spots. This should result in strong and possibly unsteady thermal stresses in the walls, which may cause rapid deterioration of wall

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material and even loss of structural integrity of the blanket [2]. In this sense, the convection effect is highly undesirable and may even require substantial modification of the currently pursued blanket designs, such as DCLL [13] or HCLL [14].

The studies of convection have so far concerned the models of blankets with poloidal ducts. The just mentioned undesirable effects of convection invite us to revisit the old concept of a blanket with toroidal channels [15,16]. In such a blanket, all or some of the channels are oriented parallel to the main (toroidal) component of the magnetic field. Active work on such blankets was carried out in the 1980s and 1990s [17]. It was focused on the self-cooled blanket concept and eventually abandoned due to a combination of reasons, such as the difficulty of electrical insulation of the walls, MHD pressure drop in manifolds, and inter-duct electromagnetic coupling (the Madrame effect) [18]. Remarkably, the effect of thermal convection was ignored in these studies. It was incorrectly assumed that the suppression by the magnetic field would lead to laminar steady-state flow fully determined by the balance between the pressure, Lorentz, and viscous friction forces, and with only passive heat transfer.

The first attempt to analyze the role of thermal convection in toroidal ducts was made in our recent work [1]. We have considered a hypothetical flow in a toroidal duct with volumetric internal heating due to the interaction between high speed neutrons and the breeder. The system was assumed to be cooled by auxiliary cooling circuits within the walls. The mean flow through the duct was taken to be negligibly weak (just sufficient for tritium transport but insignificant in the other aspects) and the walls were assumed to be maintained at a constant temperature. The key finding of [1] is that the thermal convection causes turbulence at the Grashof and Hartmann numbers typical for the reactor conditions. Due to the strong toroidal magnetic field, the flow is either purely two-dimensional (2D) or nearly 2D with weak three-dimensional (3D) perturbations superimposed on the 2D velocity. The turbulence results in strong and nearly uniform heat transfer into the walls. The turbulent mixing also removes the strong gradient of temperature and, thus, the reason for development of high-amplitude temperature fluctuations found in poloidal ducts.

This paper and the accompanying paper [19] continue the investigation. Our goal is to determine whether the promise of convection-induced turbulence detected in the idealized model of [1] is also demonstrated by more realistic systems. Toroidal duct flow with axial convective heat transfer is considered in [19]. The focus of this paper is on the validity of one model simplification used in [1], namely on taking into account only the main toroidal component of the magnetic field. In an actual blanket, there is also the weak poloidal component representing about 5% of the field strength. In the present work, we include the poloidal field and show that, at the high Hartmann numbers typical for the reactor conditions, it profoundly changes the flow behavior.

2. Physical model and numerical method

2.1. Physical model

The flow configuration is illustrated in Fig. 1. A liquid metal modeled as an incompressible and electrically conducting Newtonian fluid fills a horizontal duct of square cross-section. Steady and uniform magnetic field $\boldsymbol{B}=B_t\boldsymbol{e}_x+B_p\boldsymbol{e}_z$ is imposed in the flow domain. Here, the axial component B_t represents the main toroidal component. The poloidal component B_p is vertical and has the amplitude $B_p=0.05B_t$. Presence of this component is the new feature of the model in comparison with [1], where $\boldsymbol{B}=B_t\boldsymbol{e}_x$ is used.

The duct walls are electrically perfectly insulating and maintained at the constant temperature T_0 (see Fig. 1b). There is no mean flow along the duct. This can be considered as a conceptual simplified model of the flow and heat transfer in a toroidal duct, in which cooling is predominantly accomplished by auxiliary (e.g. pressurized He) circuits built into walls, and the mean flow of liquid metal along the duct is only needed for purification and tritium extraction and, therefore, is negligibly slow. Neutron heating load is modeled as non-uniform internal heating of volumetric rate $Q_0q(y)$ decreasing exponentially with the distance from the wall facing the reaction zone (see Fig. 1c).

We assume that the duct is long, so, as a model approximation, the effect of its ends is neglected. Both 3D flows with periodicity imposed at the x-boundaries and 2D flows independent of the x-coordinate are considered. It has been found in [1] that the strong axial magnetic field suppresses the velocity gradients in the x-direction, so the flow becomes 2D or strongly anisotropic. For each duct length L_x and Grashof number Gr, there is a critical Hartmann number Ha_{cr} such that the flow is purely 2D at $\mathrm{Ha}>\mathrm{Ha}_{cr}$. Three-dimensionality occurs at $\mathrm{Ha}<\mathrm{Ha}_{cr}$. If Ha is still large, however, the effect of three-dimensionality is not strong. The kinetic energy of 3D perturbations remains small compared to the energy of the 2D part of the flow. The conclusion of [1] is that the assumption of two-dimensionality leads to reasonably accurate results at the practically interesting values of Gr, Ha and L_x. As discussed in Section 3, a similar conclusion is reached in this study.

We use the duct's half-width d as the length scale, $\Delta T=Q_0d^2\kappa^{-1}$ as the temperature scale, free-fall speed $U=\sqrt{\beta g\Delta Td}$ as the velocity scale, d/U as the time scale, strength of toroidal magnetic field B_t as the scale of the magnetic field, dUB_t as the scale of the electric potential, ρU^2 as the pressure scale, and the maximum magnitude Q_0 as the scale of the internal heating rate. Here, κ and β are thermal conductivity and thermal expansion coefficient of the fluid, and g is acceleration of gravity. With the Boussinesq approximation of thermal convection and the quasi-static approximation of MHD effects, the non-dimensional governing equations are:

$$\frac{\partial \boldsymbol{u}}{\partial t}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=-\nabla p+\frac{1}{\sqrt{\mathrm{Gr}}}\nabla^2\boldsymbol{u}+T\boldsymbol{e}_z+\boldsymbol{F}_L, \tag{1}$$

$$\nabla\cdot\boldsymbol{u}=0, \tag{2}$$

$$\frac{\partial T}{\partial t}+\boldsymbol{u}\cdot\nabla T=\frac{1}{\mathrm{Pr}\sqrt{\mathrm{Gr}}}\left(\nabla^2T+q\right), \tag{3}$$

where $\boldsymbol{u}=(u,v,w)$ and T are the non-dimensional velocity and temperature deviation from the wall temperature T_0.

The non-dimensional internal heating rate is approximated as [20]

$$q=\exp(-y-1), \tag{4}$$

where the $y=-1$ marks the wall nearest to the reaction chamber.

The Lorentz force is computed as:

$$\boldsymbol{F}_L=\frac{\mathrm{Ha}^2}{\sqrt{\mathrm{Gr}}}\boldsymbol{j}\times\boldsymbol{e}_B, \tag{5}$$

where $\boldsymbol{e}_B=\boldsymbol{e}_x+0.05\boldsymbol{e}_z$ is the non-dimensional magnetic field. The electric current $\boldsymbol{j}$ is determined by the Ohm's law

$$\boldsymbol{j}=-\nabla\phi+\boldsymbol{u}\times\boldsymbol{e}_B, \tag{6}$$

where the electric potential ϕ is as a solution of the Poisson equation expressing the instantaneous electric neutrality of the fluid:

$$\nabla^2\phi=\nabla\cdot(\boldsymbol{u}\times\boldsymbol{e}_B). \tag{7}$$

The boundary conditions at the walls are those of perfect electric insulation

$$\frac{\partial\phi}{\partial n}=0 \quad \text{at} \quad y=\pm1, \quad z=\pm1, \tag{8}$$