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Numerical study of the MHD flow around a bounded heating cylinder: Heat transfer and pressure drops

Alessandro Tassone, Matteo Nobili, Gianfranco Caruso*

Department of Astronautical, Electrical and Energy Engineering, "Sapienza" University of Rome, Corso Vittorio Emanuele II 244, 00186 Rome, Italy

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ABSTRACT

This work studies numerically the flow around an electrically insulated heating cylinder, bounded by walls of non-uniform electrical conductivity and subjected to a transversal magnetic field, with non-null components in the toroidal and poloidal directions. The configuration is representative of a typical breeding blanket segment in tokamak fusion reactors: to minimize magnetohydrodynamic (MHD) pressure drops, the liquid metal can be employed just as tritium breeder, whereas a non-conductive secondary fluid is used as coolant. The coolant is carried in the breeding zone by pipes that, being transversal to the stream-wise direction, affect the flow features and heat transfer. The flow is investigated by simulations performed in a 3D domain for Reynolds number 20 and 40, $0 \le M \le 50$ for the Hartmann number and $0^{\circ} \le \alpha \le 32^{\circ}$ for the magnetic field inclination on the toroidal axis. The transition to the MHD regime causes the suppression of the cylinder wake and the disappearance of the steady vortex structures. Electromagnetic coupling balances the flow rates between the top and bottom sub-channels, individuated by the cylinder. The flow pattern modifications affect the heat transfer, which is found to increase with both M and α in the considered range, albeit for the latter in a non-monotonic trend. The pressure drop in the channel exhibits a similar behaviour. Moreover, it is dominated by the fully developed component due to the 2D currents, whereas the cylinder pressure drop contribution decreases steadily with the intensity of the applied magnetic field. The simulations were performed with ANSYS CFX-15.

1. Introduction

Magnetohydrodynamic (MHD) flows are employed in a wide range of industrial applications, among which the most important are metallurgy, power generation, materials science, electromagnetic pumps and flow meters [1]. In nuclear fusion applications, a blanket is used for several critical functions including: the removal of the heat deposited by the fusion neutrons, the plasma-facing first wall refrigeration, the breeding of the tritium required for the reactor operation and the radiation shielding for sensible components (i.e. superconducting coils) and personnel. Due to the extreme thermal loads involved in the reactor operation (several MW/m^2), liquid metals (LM) are considered as ideal blanket working fluids due to their excellent thermal properties and the possibility to fulfill the roles of tritium breeder and neutron multiplier for alloys containing Li [2,3]. However, significant unresolved technological issues are connected to the use of these fluids, one of the most important being the interaction with the plasma confinement magnetic field, which results in the transition to a magnetohydrodynamic (MHD) flow regime.

Typically, the flow of the LM in a fusion blanket can be reduced to a rectangular duct flow in the presence of a strong, transverse, external magnetic field. The fluid motion induces the formation of electric currents which, in turn, interact with the magnetic field to generate Lorentz forces. These exert a retarding action, which can be considered as an additional electromagnetic "drag" term, and modify the flow features, interfering with the heat and mass transport mechanisms [4]. Enhanced corrosion rates of structural materials, turbulence suppression and pressure drops increased by orders of magnitude compared with the hydrodynamic case are among the most important challenges faced by the fusion blanket design [5–9].

To counter this last issue, a common strategy is to minimize the LM velocity, therefore delegating the blanket cooling to a secondary, non-conductive, fluid as water or helium. This solution leads to the necessity to devise a coolant system layout that can efficiently refrigerate the LM that, in this configuration, is considered just as tritium breeder. Most often encountered solutions employ cooling plates or pipes that tailor the LM flow or are immersed in it, both in the stream wise and transverse direction [10–12].

The bounded pressure-driven flow past a circular cylinder is a classic case studied in hydrodynamics and recently it has been

* Corresponding author.
E-mail address: gianfranco.caruso@uniroma1.it (G. Caruso).

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Nomenclature

A	cylinder area [m^2]
B	magnetic induction (intensity) [T]
c_p	specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
d	cylinder diameter [m]
F	stream-wise length [m]
G	distance between cylinder bottom and lower wall [m]
H	poloidal half-length [m]
J	current density [$A\ m^{-2}$]
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
L	toroidal half-length [m]
p	pressure [Pa]
r, θ, z	cylindrical coordinates [m, rad, m]
x, y, z	Cartesian coordinates [m]
T	temperature [K]
u_0	inlet mean velocity [$m\ s^{-1}$]

Greek symbols

α	magnetic field inclination [°]
β	blockage ratio [−]
δ	thickness [m]
μ	magnetic permeability [$H\ m^{-1}$]
ν	kinematic viscosity [$m^2\ s^{-1}$]
σ	electrical conductivity [$S\ m^{-1}$]
ϕ	electric potential [V]

Dimensionless groups

c	wall conductance ratio
M	Hartmann number
N	Stuart number
Pe	Péclet number
Pr	Prandtl number
Re	Reynolds number

Subscripts

b	bottom wall, bulk
d	downstream
H	Hartmann layer
m	magnetic
s	side walls
t	top wall
u	upstream
w	wall

investigated in a MHD perspective. The blockage ratio (β) and the offset from the duct centreline (G/d) are the most important geometric parameters and, together with the dimensionless Reynolds number (Re), Hartmann number (M, ratio between electromagnetic and viscous forces) and wall conductance ratio (c, ratio between duct wall and fluid electrical conductivity), define the flow features. The case of a magnetic field transverse to the flow and aligned with the cylinder axis is particularly important for fusion blankets applications and has been studied in the past both experimentally and numerically. The magnetic field is found to retard the transition to unsteady and turbulent regimes, suppress the cylinder wake and, in general, stabilize the flow compared with the hydrodynamic case [13–16].

The aim of this study is to extend the knowledge available for this class of flows by investigating the effect of features that, although commonly encountered in blanket design, have been not sufficiently investigated in the literature such as skewed magnetic field, bounding duct walls of non-uniform thickness and finite conductivity obstacles. The dynamics and heat transfer characteristics of a 3D MHD flow past a confined cylinder in a strong magnetic field were studied for Re = 20 and 40, Hartmann number in the range $0 \le M \le 50$ and $0° \le \alpha \le 32°$ for the magnetic field inclination on the toroidal axis.

2. Formulation

The problem geometry is shown in Fig. 1. A rectangular duct with toroidal half-length L and poloidal half-length H confines a circular cylinder of diameter d. The coordinate system (x, y, z) identifies the radial (streamwise), poloidal and toroidal directions and has its origin in the obstacle centre.

A local cylindrical coordinate system with the same origin (r, θ, z) is

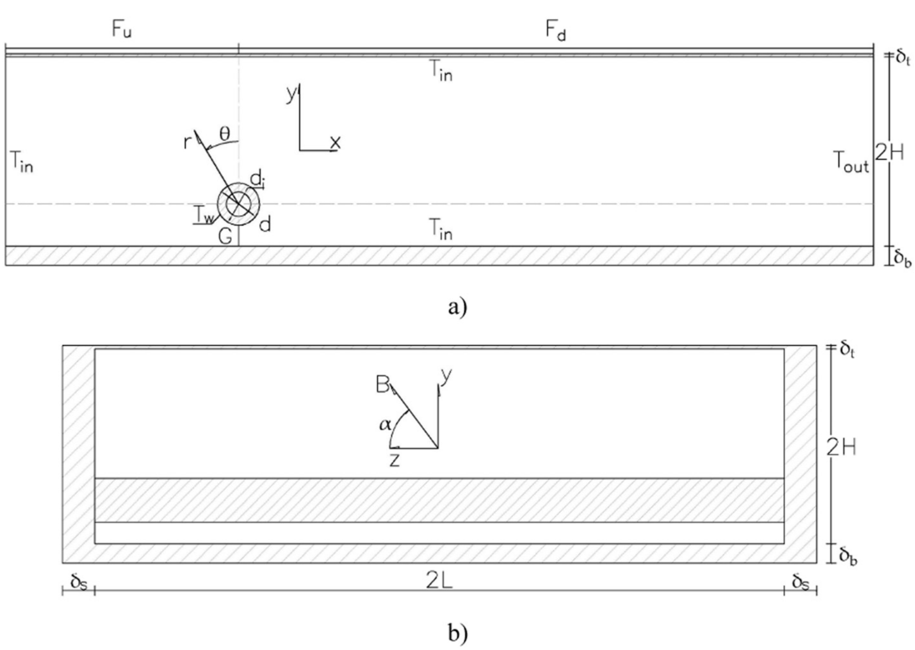

Fig. 1. Test case geometry: a) radial-poloidal cross-section, the inlet is located at the left of the cylinder (x-direction); b) toroidal-poloidal cross-section (view from the inlet).