Nuclear Engineering and Technology xxx (2016) 1–10

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Invited Article

First Studies for the Development of Computational Tools for the Design of Liquid Metal Electromagnetic Pumps

Carlos O. Maidana [a,b,c,*] and Juha E. Nieminen [a,d]

[a] Maidana Research, 2885 Sanford Ave SW #25601, Grandville, MI 49418, USA
[b] Idaho State University, Department of Mechanical Engineering, Pocatello, ID 83209, USA
[c] Chiang Mai University, Department of Mechanical Engineering, Chiang Mai 50200, Thailand
[d] University of Southern California, Department of Astronautical Engineering, Los Angeles, CA 90089, USA

ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form
24 May 2016
Accepted 16 July 2016
Available online xxx

Keywords:
ALIP
Electromagnetic Pumps
Liquid Metals
Magneto–Hydrodynamics
Thermo–Magnetic Systems

ABSTRACT

Liquid alloy systems have a high degree of thermal conductivity, far superior to ordinary nonmetallic liquids and inherent high densities and electrical conductivities. This results in the use of these materials for specific heat conducting and dissipation applications for the nuclear and space sectors. Uniquely, they can be used to conduct heat and electricity between nonmetallic and metallic surfaces. The motion of liquid metals in strong magnetic fields generally induces electric currents, which, while interacting with the magnetic field, produce electromagnetic forces. Electromagnetic pumps exploit the fact that liquid metals are conducting fluids capable of carrying currents, which is a source of electromagnetic fields useful for pumping and diagnostics. The coupling between the electromagnetics and thermo-fluid mechanical phenomena and the determination of its geometry and electrical configuration, gives rise to complex engineering magnetohydrodynamics problems. The development of tools to model, characterize, design, and build liquid metal thermo-magnetic systems for space, nuclear, and industrial applications are of primordial importance and represent a cross-cutting technology that can provide unique design and development capabilities as well as a better understanding of the physics behind the magneto-hydrodynamics of liquid metals. First studies for the development of computational tools for the design of liquid metal electromagnetic pumps are discussed.

1. Introduction

The coupling between the electromagnetic and thermo-fluid mechanical phenomena observed in liquid metal thermo-magnetic systems, and the determination of the device geometry and electrical configuration, gives rise to complex engineering magneto-hydrodynamics (MHD) and numerical problems that we aim to study, where techniques for global optimization are to be used, MHD instabilities understood, and multiphysics models developed and analyzed. The

* Corresponding author.
E-mail addresses: carlos.omar.maidana@maidana-research.ch, maidanac@gmail.com (C.O. Maidana).
http://dx.doi.org/10.1016/j.net.2016.07.002

Please cite this article in press as: C.O. Maidana, J.E. Nieminen, First Studies for the Development of Computational Tools for the Design of Liquid Metal Electromagnetic Pumps, Nuclear Engineering and Technology (2016), http://dx.doi.org/10.1016/j.net.2016.07.002

environment of operation adds further complexity, i.e., vacuum, high temperature gradients, and radiation, whilst the presence of external factors, such as the presence of time and space varying magnetic fields, also leads to the need for the development of active flow control systems. The development of analytical models and predictive tools to model, characterize, design, and build liquid metal thermo-magnetic systems and components for space, nuclear, and industrial applications are of primordial importance and represent a cross-cutting technology that can provide unique design and development capabilities, as well as a better understanding of the physics behind the magneto-hydrodynamics of liquid metals and plasmas.

2. Liquid metal technology for nuclear fission reactors

Liquid metal-cooled reactors are both moderated and cooled by a liquid metal solution. These reactors are typically very compact and can be used for regular electric power generation in isolated places, for fission surface power units for planetary exploration, for naval propulsion, and as part of space nuclear propulsion systems. Certain models of liquid metal reactors are also being considered as part of the Generation-IV nuclear reactor program. The liquid metal thermo-magnetic systems used in this type of reactor are MHD devices, of which the design, optimization, and fabrication represent a challenge due to the coupling of the thermo-fluids and the electromagnetics phenomena, the environment of operation, the materials needed, and the computational complexity involved.

A liquid metal-cooled nuclear reactor is a type of nuclear reactor, usually a fast neutron reactor, where the primary coolant is a liquid metal. While pressurized water could theoretically be used for a fast reactor, it tends to slow down neutrons and absorb them which limits the amount of water that can flow through the reactor core. Fast reactors have a high power density, therefore most designs use molten metals instead. The boiling point of water is also much lower than most metals, demanding that the cooling system be kept at high pressure to effectively cool the core. Another benefit of using liquid metals for cooling and heat transport is its inherent heat absorption capability.

Liquid metals also have the property of being very corrosive and bearing, seal, and cavitation damage problems associated with impeller pumps in liquid-metal systems mean they are not an option so electromagnetic pumps are used instead. In all electromagnetic pumps, a body force is produced on a conducting fluid by the interaction of an electric current and a magnetic field in the fluid. This body force results in a pressure rise in the fluid as it passes from the inlet to the outlet of the pump.

In space reactors, as well as in other types of semi-transportable small modular reactors, weight, reliability, and efficiency are of fundamental importance. Furthermore, liquid metals are the only option for the working fluid in space reactors due to the working environment characteristics that outer space provides. In space power systems, the induction electromagnetic pump is inherently more reliable than the conduction electromagnetic pump because it lacks electrodes. The annular linear induction pump (ALIP) has several advantages over its flat counterpart because it has greater structural integrity, is more adaptable to normal piping systems, and allows greater design freedom in the coil configuration. The annular design also has a basically greater output capability because the path followed by the induced currents has a lower resistance than the path followed in a corresponding flat pump.

3. Fundamental equations

The equations describing the liquid metal dynamics are given by:

$$J_i = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \tag{1}$$

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\mathbf{u}\right] + \nabla p - \rho\nu\nabla^2\mathbf{u} = \mathbf{J}\times\mathbf{B} \tag{2}$$

where the current density is $\mathbf{J} = \mathbf{J}_s + \mathbf{J}_i$, σ and ν are the conductivity and kinematic viscosity (ratio of the viscous force to the inertial force) of the fluid, $\mathbf{J}_i$ is the liquid metal-induced density current, $\mathbf{J}_s$ is the surface current density, and $\mathbf{u}$ is the fluid velocity. The linear momentum of the fluid element could change not only by the pressure force, $-\nabla p$, viscous friction, $\rho\nu\nabla^2\boldsymbol{u}$, and Lorentz force, $\boldsymbol{J}\times\boldsymbol{B}$, but also by volumetric forces of nonelectromagnetic origin; then Eq. [2] should be modified and it could be expressed with an additional term $\boldsymbol{f}$ in the right hand side:

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\mathbf{u}\right] + \nabla p - \rho\nu\nabla^2\mathbf{u} - \mathbf{f} = \mathbf{J}\times\mathbf{B} \tag{3}$$

while the conservation of mass for liquid metals would be given by $\nabla\cdot\boldsymbol{u} = 0$, which expresses the incompressibility of the fluid. An induction equation, valid in the domain occupied by the fluid and generated by the mechanical stretching of the field lines due to the velocity field, can be written as:

$$\frac{\partial}{\partial t}\boldsymbol{B} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{B} = \frac{1}{\mu\sigma}\nabla^2\boldsymbol{B} + (\boldsymbol{B}\cdot\nabla)\boldsymbol{u} \tag{4}$$

describing the time evolution of the magnetic field $\partial B/_{\partial t}$, due to advection $(\boldsymbol{u}\cdot\nabla)\boldsymbol{B}$, diffusion $\nabla^2\boldsymbol{B}$, and field intensity sources $(\boldsymbol{B}\cdot\nabla)\boldsymbol{u}$. Sometimes the induction equation, Eq. [4], is written dimensionless by the introduction of scale variables and as a function of the magnetic Reynolds number $R_m = \mu\sigma L u_0$, where u_0 is the mean velocity and L the characteristic length. A relatively small R_m generates only small perturbations on the applied field; if R_m is relatively large then a small current creates a large induced magnetic field. For small magnetic Reynolds numbers (R_m<<1), the magnetic field will be dominated by diffusion and perturbative methods can be used accurately. Similarly, the equation for temperature is:

$$\rho c_p\left[\frac{\partial}{\partial t}T + (\boldsymbol{u}\cdot\nabla)T\right] = \nabla\cdot(\lambda\nabla T) + \frac{1}{\sigma}J^2 + \Phi + Q \tag{5}$$

which is a convection-diffusion equation where λ is thermal conductivity, Q is other sources of volumetric energy release such as radiation or chemical reactions and thermal

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