Multiphysics Analysis of Liquid Metal Annular Linear Induction Pumps: A Project Overview

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Abstract. Liquid metal-cooled fission reactors are both moderated and cooled by a liquid metal solution. These reactors are typically very compact and they can be used in regular electric power production, for naval and space propulsion systems or in fission surface power systems for planetary exploration. The coupling between the electromagnetics and thermo-fluid mechanical phenomena observed in liquid metal thermo-magnetic systems for nuclear and space applications gives rise to complex engineering magnetohydrodynamics and numerical problems. It is known that electromagnetic pumps have a number of advantages over rotating mechanisms: absence of moving parts, low noise and vibration level, simplicity of flow rate regulation, easy maintenance and so on. However, while developing annular linear induction pumps, we are faced with a significant problem of magnetohydrodynamic instability arising in the device. The complex flow behavior in this type of devices includes a time-varying Lorentz force and pressure pulsation due to the time-varying electromagnetic fields and the induced convective currents that originates from the liquid metal flow, leading to instability problems along the device geometry. The determinations of the geometry and electrical configuration of liquid metal thermo-magnetic devices give rise to a complex inverse magnetohydrodynamic field problem were techniques for global optimization should be used, magnetohydrodynamics instabilities understood –or quantified- and multiphysics models developed and analyzed.

We present a project overview as well as a few computational models developed to study liquid metal annular linear induction pumps using first principles and the a few results of our multi-physics analysis.

Keywords: liquid metals, magneto-hydrodynamics, thermo-magnetic systems, electromagnetic pumps, ALIP.

INTRODUCTION

The coupling between the electromagnetics 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 magnetohydrodynamics and numerical problems that we aim to study, were techniques for global optimization has to be used, MHD instabilities understood, and multiphysics models developed and analyzed. The environment of operation adds even 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 of developing 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 besides a better understanding of the physics behind the magneto-hydrodynamics of liquid metals and plasmas.

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 reactors are MHD devices which design, optimization and fabrication represents 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. This challenge we aim to solve.

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. This limits the amount of water that can be allowed to flow through the reactor core, and since fast reactors have a high power density 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 make them not an option and electromagnetic pumps are used instead. In all electromagnetic pumps, a body forced is produced on a conducting fluid by the interaction of an electric current and 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, for the former, liquid metals as working fluid are the only option due to the working environment characteristics that outer space provides. For space power systems, the induction electromagnetic pump, because it lacks electrodes, is inherently more reliable than the conduction electromagnetic pump. The annular linear induction pump, furthermore, 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 since the path followed by the induced currents has a lower resistance than the path followed in a corresponding flat pump.

LIQUID METAL TECHNOLOGY FOR NUCLEAR FUSION REACTORS

Research and development in nuclear fusion devices is increasing worldwide and experimental facilities and prototypes face new engineering magnetohydrodynamics challenges and needs. Among the latter are the use of liquid metals thermomagnetic systems such as electromagnetic pumps and the use of liquid metals as plasma facing material. Certain engineering MHD problems and solutions are shared by different fields but there are aspects specific to nuclear fusion devices that we aim to solve by developing mathematical, computational and experimental methods and tools useful in the design and multi-physics analysis of engineering components and in the understanding of the MHD phenomena in place.

Despite many differences between possible designs of power plant, there are several systems that are common to most. A fusion power plant, like a fission power plant, is customarily divided into the nuclear island and the balance of plant. The balance of plant converts heat into electricity via steam turbines; it is a conventional design area and in principle similar to any other power station that relies on heat generation, whether fusion, fission or fossil fuel based. The nuclear island has a plasma chamber with an associated vacuum system, surrounded by plasma-facing components (first wall and divertor) maintaining the vacuum boundary and absorbing the thermal radiation coming from the plasma, itself surrounded by a "blanket" where the neutrons are absorbed to breed tritium and heat a working fluid that transfers the power to the balance of plant. If magnetic confinement is used, a magnet system is needed, and usually systems for heating and refueling the plasma and for driving current. In inertial confinement, a driver (laser or accelerator) and a focusing system are needed, as well as a mean for forming and positioning the pellets.

The plasma-facing material is any material used to construct the plasma-facing components, those components exposed to the plasma within which nuclear fusion occurs, and particularly the material used for the lining or first wall of the reactor vessel. The plasma facing components in energy producing fusion devices will experience 5-15 MW/m^2 surface heat flux under normal operation (steady-state) and off-normal energy deposition up to 1 MJ/m^2 within 0.1 to 1.0 ms. Refractory solid surfaces represent one type of plasma facing component option. Another option is to use a flowing liquid metal surface as a plasma facing component, an approach which will require the production and control of thin, fast flowing, renewable films of liquid metals such as lithium, gallium, or tin for particle control at diverters.

FUNDAMENTAL EQUATIONS

The equations describing the liquid metal dynamics are given by:

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

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

where the current density is $\mathbf{J}=\mathbf{J}_s+\mathbf{J}_i$, s and n are the conductivity and kinematic viscosity (ratio of the viscous force to the inertial force) of the fluid, and **u** is the fluid velocity. Because 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 non-electromagnetic origin; then eq. (2) should be modified and it could be expressed with an additional term $\boldsymbol{f}$ in the right hand side,

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

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,

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

describing the time evolution of the magnetic field, $\partial\boldsymbol{B}/\partial t$, 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

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

which is a convection-diffusion equation with l*:* thermal conductivity, *Q:* other sources of volumetric energy release such as radiation or chemical reactions and thermal diffusivity $k = \lambda/\rho c_p$, c_p*:* constant pressure specific heat of the flow*;* while the kinetic energy evolution is given by,

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho u^2\right) = -\nabla\cdot\left[\boldsymbol{u}\left(p + \frac{1}{2}\rho u^2\right) - \boldsymbol{u}\cdot\boldsymbol{S}\right] + \boldsymbol{u}\cdot(\boldsymbol{J}\times\boldsymbol{B}) + \boldsymbol{u}\cdot\boldsymbol{f} - \Phi, \quad (6)$$

where **S** is the viscous stress tensor. We deduce from the latter that due to the action of the Lorentz forces an increase of the kinetic energy leads to a decrease in the magnetic energy. From the temperature equation, eq. (5), one can identify the temporal increase of enthalpy, $\rho c_p \frac{\partial T}{\partial t}$, which equals to the loss of magnetic energy due to joule dissipation, $\frac{1}{\sigma}J^2$, plus the loss of kinetic energy, F, due to viscous dissipation.

From the mathematical point of view, the coupling between Maxwell equations and Navier-Stokes equations induces an additional nonlinearity with respect to the ones already present, leading to unsolved questions of existence and uniqueness (mainly related to the hyperbolic nature of Maxwell equations). As explained by Gerbeau et al., simplified models can be analyzed but care should be taken with certain approximations:

A system coupling the time dependent incompressible Navier-Stokes equations with a simplified form of the Maxwell equations (low frequency approximation) is well-posed when the electromagnetic equation is taken to be time-dependent, i.e. parabolic form. In contrast, the same model is likely to be ill-posed when the electromagnetic equation is taken to be time-independent, i.e. elliptic form, while the hydrodynamic equations are still in a time dependent form.

The coupling of Maxwell equations with Navier-Stokes equations certainly represents a challenge.

ANNULAR LINEAR INDUCTION PUMPS

A special type of liquid metal thermo-magnetic device is the annular linear induction pump. It is known that electromagnetic pumps have a number of advantages over mechanical pumps: absence of moving parts, low noise and vibration level, simplicity of flow rate regulation, easy maintenance and so on. However, while developing a large-scale induction pump, in particular annular linear induction pumps (ALIPs), we are faced with a significant problem of magnetohydrodynamic instability arising in the device. The manifestation of the instability does not allow linear induction pump development in a certain range of flow rate or the development of high efficiencies under certain flow rates and dropping pressure conditions.

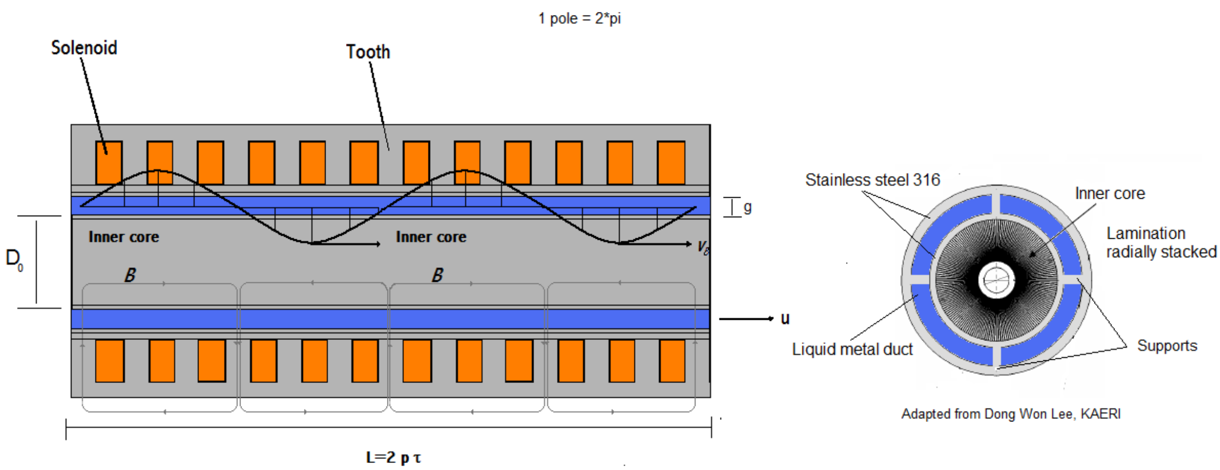

Figure 1: Cross sections of an annular linear induction pump (conceptual representation).

Linear induction pumps use a traveling magnetic field wave, Fig. 1, created by 3-phase currents, and the induced currents and their associated magnetic fields that generate a Lorentz force. The three-phase winding arrangement for the solenoids usually follows the sequence AA ZZ BB XX CC YY where A, B, C denote the balanced three-phase winding and X, Y, Z the opposite phase; for a direct balanced system, if A: 0º, B:120º and C:240º then X:180º, Y:300º and Z:60º. Arranging the sequence by rising phase, one obtain the correct winding sequence for the solenoids: AA ZZ BB XX CC YY. The complex flow behavior in this type of devices includes a time-varying Lorentz force and pressure pulsation due to the time-varying electromagnetic fields and the induced convective currents that originates from the liquid metal flow, leading to instability problems along the device geometry. The determination of the geometry and of the electrical configuration of a thermo-magnetic device gives rise to an inverse magnetohydrodynamic field problem. When the requirements of the design are defined, this problem can be solved by an optimization technique. The objective function which has to be maximized in the optimization problem is derived from the main design requirement. Usually for a magnetohydrodynamic device, this is the efficiency. Other design requirements can be taken into account as constraints. For a non-linear system, such as for linear induction pumps, the main objective functions are low weight and high efficiency and so more than one maximum can exist. In this case a technique for the global optimization has to be used. Before any optimization method can be used, design approaches should be identified and understood while mathematical and computational models developed. This leads to the study of magnetohydrodynamics instabilities, usually with negative effects on the efficiency and working fluid behavior, as well as to the study of its individual components, its fabrication methods, assembly and system integration procedures.

PROJECT OBJECTIVES AND METHODOLOGY

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 besides a better understanding of the physics behind the magneto-hydrodynamics of liquid metals and plasmas. The complexity of the MHD equations had made impossible to develop a design and optimization methodology using first-principles as well as to perform a true multi-physics analysis where the couple phenomena is studied as a whole. The approached used until today is to approximate the system behavior by using the electric-circuit-approach for electric machines which cannot give a realistic inside to the physics phenomena that takes place and can neither leads to a reliable design methodology nor to the determination of reliable operational working points by itself. The increased in computational power, at software and hardware level, as well as the theoretical, computational, and experimental effort performed during the last years by the principal investigator and a group of people in the United States, France, Japan and South Korea has led to advances in the understanding of the phenomenology and technical challenges that the engineering of MHD devices represent. We are for first time in conditions of performing this type of work designing and optimizing liquid metal thermo-magnetic systems. We aim to design liquid metal thermo-magnetic systems with emphasis in annular linear induction pumps as well as computational tools for analysis and CAE design of electromagnetic pumps of the ALIP type including measurement and control systems for diagnostics, operation and machine protection of the electrical and mechanical systems.

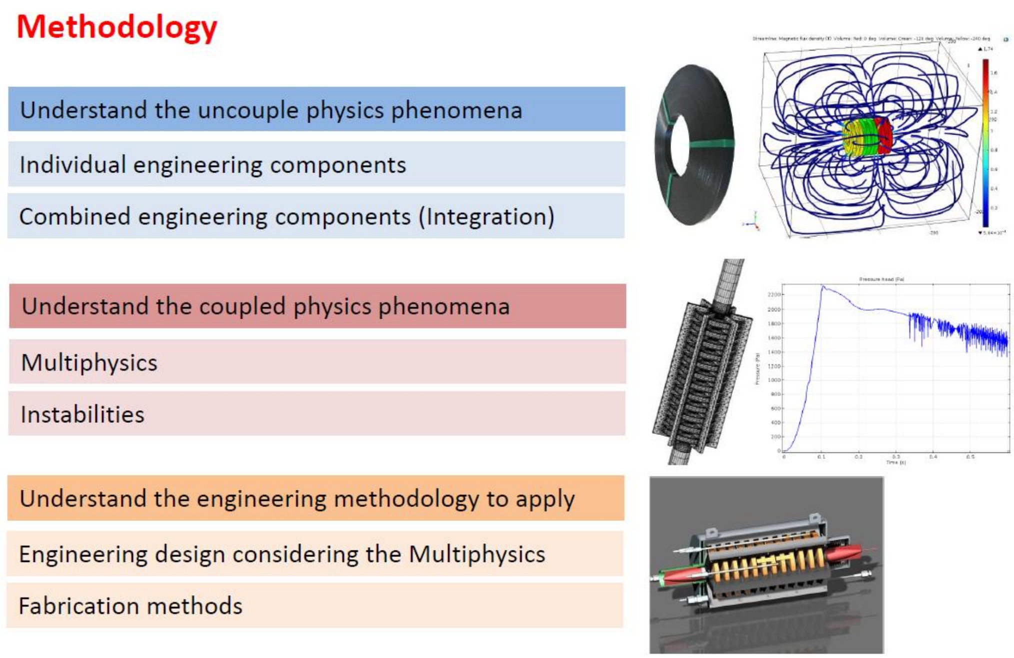

Figure 2: Modeling, simulation and analysis methodology.

For our project development we have selected COMSOL Multiphysics and MATLAB. COMSOL Multiphysics is a finite element analysis, solver and Simulation software / FEA Software package for various physics and engineering applications, especially coupled phenomena, or multiphysics. COMSOL Multiphysics also offers an extensive interface to MATLAB and its toolboxes for a large variety of programming, preprocessing and post-processing possibilities. The packages are cross-platform. In addition to conventional physics-based user interfaces, COMSOL Multiphysics also allows for entering coupled systems of partial differential equations (PDEs). The PDEs can be entered directly or using the so-called weak form (see finite element method for a description of weak formulation). MATLAB® is a high-level language and interactive environment for numerical computation, visualization, and programming. Using MATLAB, you can analyze data, develop algorithms, and create models and applications. The language, tools, and built-in math functions enable you to explore multiple approaches and reach a solution faster than with spreadsheets or traditional programming languages, such as C/C++ or Java. COMSOL Multiphysics is integrated with MATLAB via the LiveLink for MATLAB, which lets you generate a MATLAB file version of a simulation built with COMSOL Multiphysics. We can modify the model MATLAB file, extend it with MATLAB code, and run it from MATLAB which can allow the compilation of specific models that can be used independently as well as for the development of a low order model of the MHD flow. MATLAB can be used for the development of active flow control, machine protection and other general control systems using model-based design.

Once our analysts and researchers complete their simulation model we will be able to package it into an application using the Application Builder. This app will feature a custom made interface and control method designed by our analysts and researchers for our clients, co-workers, collaborators, students, and more. By using COMSOL Server as a hub that will enable the sharing and running of simulation applications. Apps can be run from anywhere in the world and on multiple computers, can save the end user's input changes directly through the server, and allow colleagues and customers access to the simulation expertise of design and engineering teams, Fig. 2.

Our modeling, simulation and analysis methodology can be divided in three parts: i) understanding the uncoupled physics phenomena, ii) understanding the coupled physics phenomena and iii) understanding of the engineering methodology to use. The first part can be sub-divided in modeling individual engineering components and simulating, analyzing and validating the results. After the main individual components where modeled, then the modeling, simulation and analysis of combined engineering components was performed analyzing the results of the integration process with uncoupled physical processes. The second part can be divided in simulating the coupled physical processes (multiphysics) and analyzing its behavior. Instabilities naturally come out of the coupling and validation with experimental data available can be performed. The third part is related to the construction of the ALIP where structural integrity issues, instrumentation type and location, and construction, assembly, operation and machine protection issues should be considered and used as constraints or feedback when needed.

PARTIAL RESULTS

We have studied, modeled and simulated the solenoids that represent the core of the annular linear induction pumps. A strong dependency on frequency has been found where the lower the frequency the higher the magnetic field available for Lorentz force pumping. A possible non-desired effect of working on lower frequency range is the increased of the edge effect on the solenoidal cell. Large fringe fields are found besides the excitation frequency of the system. These fringe fields should be minimize using a stator sections but they can be identified as a source of instabilities at the inlet and outlet of electromagnetic pumps, Fig. 3.

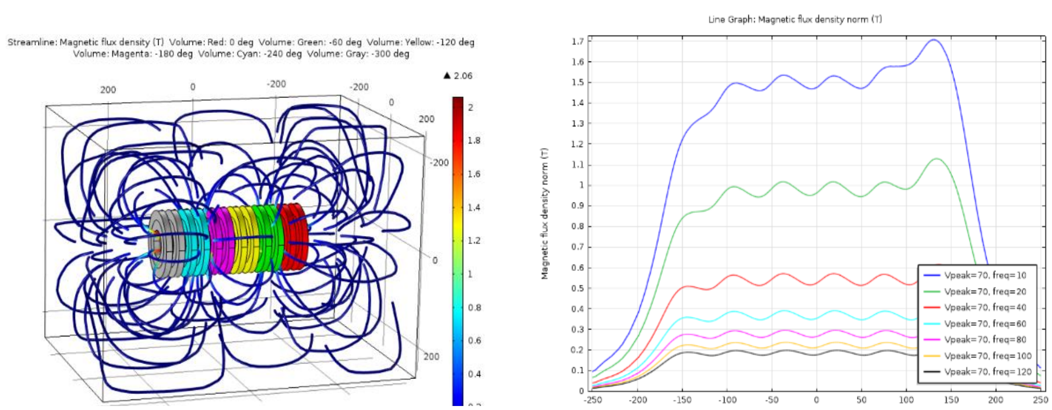

Figure 3: Model and simulations results for 12 solenoids powered by a 3-phase system. A strong frequency dependence on the magnetic field (average) is observed. The lower the frequency the largest the magnetic field.

After studying the individual components and some uncouple phenomena, we modeled, simulated and analyzed the behavior of a one pole pair, 6 solenoids, Sodium pump with different core sizes. The model employs the full 3D geometry of the pump and the cooling loop, and couples electromagnetic and turbulent fluid dynamics to simulate the flow in the closed system. A time-dependent study was used, time step being 1/16 of the full excitation voltage cycle to capture the temporal variation of Lorentz force that produces the pumping action. A study of the pressure head developed, shows the development of instabilities on a short period of time. The specific instability found as a result of our simulations is known as a double-frequency pulsation and it is found in most annular linear induction pumps in operation, Fig. 4. This result is useful for partial validation of the modeling work done.

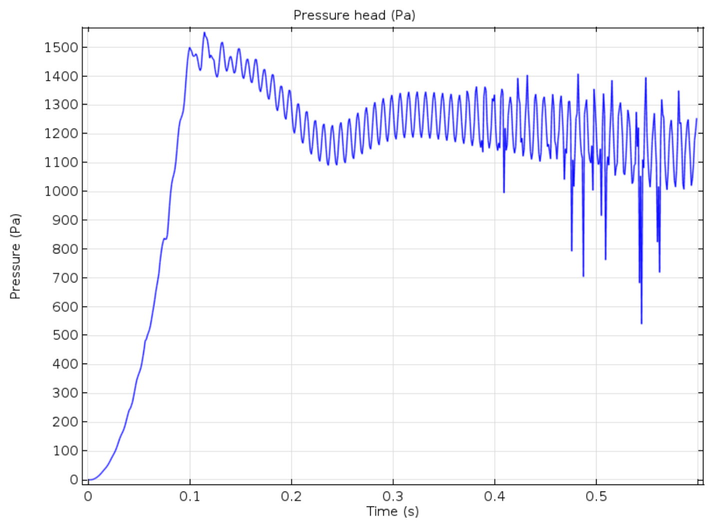

Figure 4: Pressure head versus time for a 6-coils annular linear induction pump model where the double-frequency pulsation instability can be easily seen.

Simulation of a 12 coils ALIP for different set of parameters represents a bigger computational challenge. Analysis of the pressure head for a 12 coils, 60 Hz, 70 V 3-phase system with a relatively large core shows the presence of two type of instabilities as expected, Fig. 5. The first instability is a low frequency (LF) instability which with time is superimposed to the double-frequency instability (DF). As a result of the combination of instabilities, and a complex pressure pattern is developed at inlet and outlet. But differences have been found when symmetry is wants to be exploited instead of using a full 3D model.

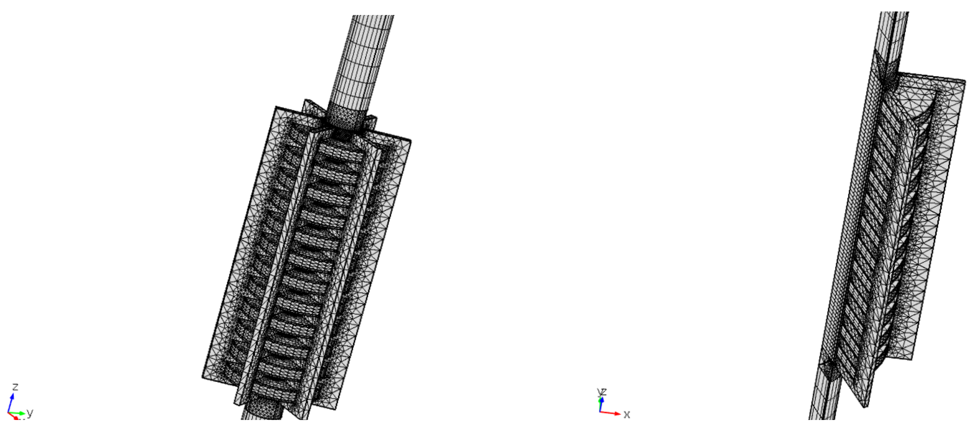

Figure 5: 3D and sliced models of annular linear induction pumps. The sliced model tries to make use of symmetries to reduce the computations but it seems not applicable or partially applicable only..

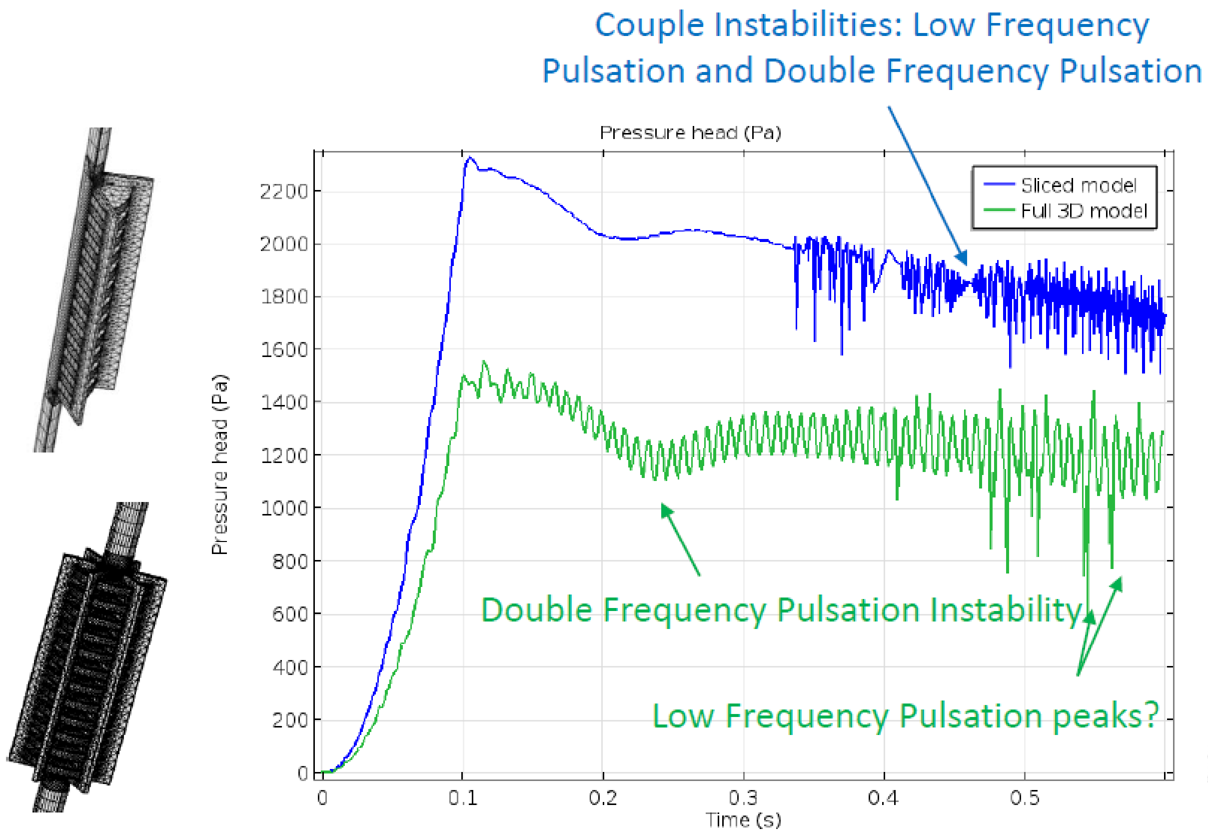

Figure 6: Comparison of pressure heads results for a 3D model simulation and a sliced model simulation. The sliced model using symmetries seems not to be able to resolve the presence of the double frequency instability by itself.

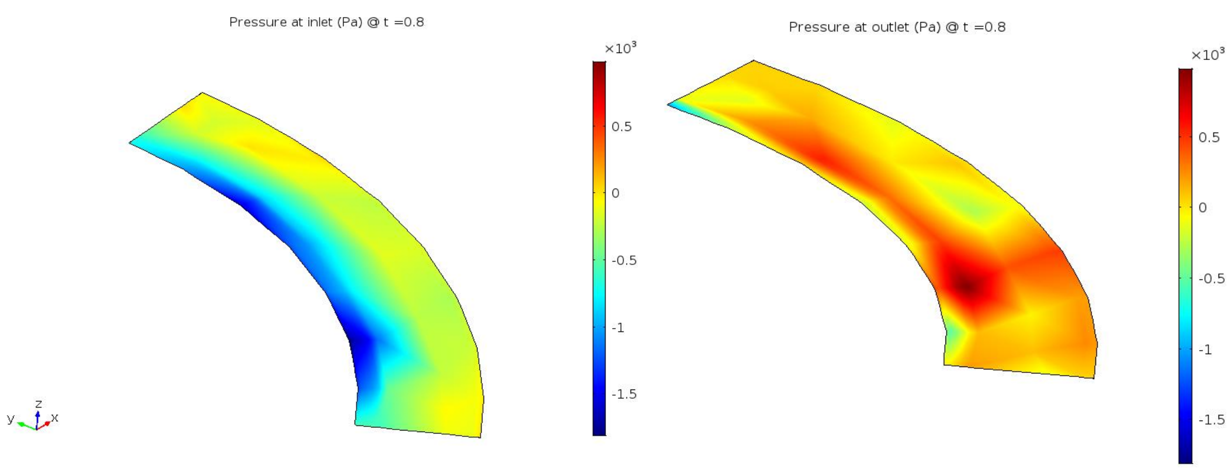

Figure 7: Pressure at inlet and outlet. It can be easily seen the inhomogeneous pressure distribution that prevent the use of symmetry.

The fringe fields generated by coils contain various nonlinearities due to the longitudinal dependence of the magnetic field. Due to the solenoids fringe fields, its finite core length and the induced currents, the ALIP has an *end effect* at both ends of the pump. A reduction on the developed force arises which is roughly equal to the product of the magnetic field and its perpendicular induced current. Theoretical calculations indicate a reduction of the end effects by controlling the input frequency; increasing the efficiency at the lower frequencies compared with results obtained at frequencies over 60 Hz. The inlet *end effect* force affects most of the pump while the outlet *end effect* domain is limited to the exit region. Considering the direct relationship between fluid velocity and *end effect,* low frequency operation is preferred as far as the developing force and the efficiency are not decreased too much. When the end effects are neglected, it is easy to show that the pump efficiency is given as the ratio of the flow velocity u to the synchronous velocity ω/κ of the fields (i.e. $n=\kappa u/\omega=1-s$). But when the end effects are included its efficiency has to be computed using numerical integration and its maximum lies in the range $0.2<s<0.4$ where s is the slip factor, Fig. 7.

Instabilities usually arise when the three conditions hold true: $R_{ms}>1$, $D/2\tau$ and N_{int} = *"large enough"*. An instability appears as a low frequency (LF) pulsation in the pressure head affecting the flow rate, liquid metal velocity and magnetic field distribution. As a consequence vortices are generated in the inlet region as well as fluctuations in the winding currents and voltages. The dominant frequency of this instability is in the range 0-10 Hz with amplitude that increases with the slip factor. This LF pressure pulsation is produced by vortices in the liquid metal generated by the no uniformity of the azimuthal component of the applied magnetic field when $R_{ms}>1$. The magnetic Reynolds number, R_{ms}, often becomes greater than unity in the pump region where the slip is larger than 0.2 giving place to another instability known as double supply frequency (DSF) pressure pulsation. The vibration caused by the DSF pressure pulsation occurs in the pump outlet and propagates to the pipe when $R_{ms}<1$ and $s<0.2$.

The thickness of the duct walls affect the efficiency of the pump due to the magnetic resistivity that presents; but it must not be too thin as too risk its structural integrity. The width of the fluid channel should be limited to below the skin depth of the fluid for stable operation. A final diagram is shown in Fig. 8.

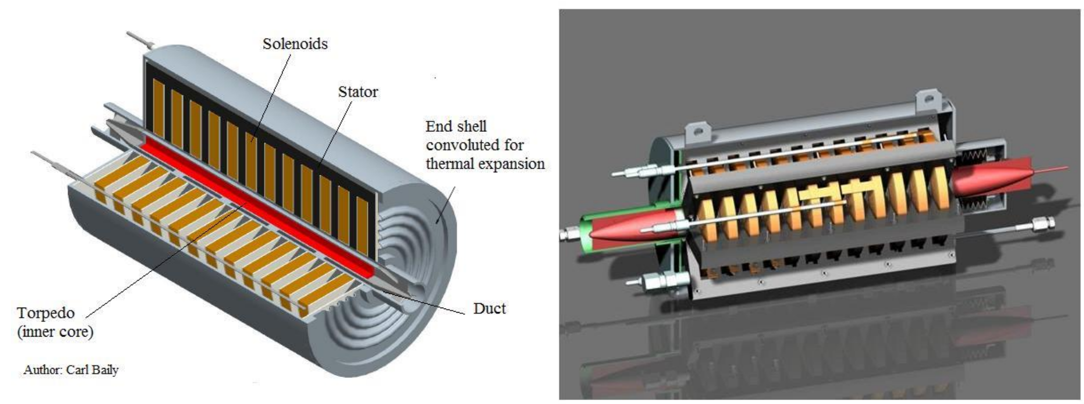

Figure 8: 3D model of the EM pump. Notice how the inner core, or torpedo, extends beyond the solenoid-stator section.

CONCLUSIONS

The complexity of the MHD equations had made impossible to develop a design and optimization methodology using first-principles as well as to perform a true multi-physics analysis where the couple phenomena is studied as a whole. The approached used until today is to approximate the system behavior by using the electric-circuit-approach for electric machines which cannot give a realistic inside to the physics phenomena that takes place and can neither leads to a reliable design methodology nor to the determination of reliable operational working points by itself. The increased in computational power, at software and hardware level, as well as the theoretical, computational, and experimental effort performed during the last years by this author and a group of people in the United States, France, Japan and South Korea has led to advances in the understanding of the phenomenology and technical challenges that the engineering of MHD devices represent. We are for first time in conditions of performing this type of work designing and optimizing liquid metal thermo-magnetic systems using first principles and multi-physics analysis.

The variety and importance of the topic leads to the need of i) developing computational tools for the study and analysis of the liquid metal MHD phenomena, ii) To a better understanding of the physics and engineering of liquid metal thermo-magnetic systems for better modeling, iii) To develop tools, procedures and CAE software for more accurate simulation of the device, iv) To develop procedures and tools for design optimization, and v) to develop control systems for active flow control.

We have shown a project overview as well as the first results. Further results will be discussed in other papers but the advances made are of fundamental importance.

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