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Engineering design of plasma generation devices using Elmer finite element simulation methods

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ABSTRACT

Plasma generation devices are important technology for many engineering disciplines. The process for acquiring experience for designing plasma devices requires practice, time, and the right tools. The practice and time depend on the individual and the access to the right tools can be a limiting factor to achieve experience and to get an idea on the possible risks. The use of Elmer finite element method (FEM) software for verifying plasma engineering design is presented as an accessible tool that can help modeling multi-physics and verifying plasma generation devices. Furthermore, Elmer FEM will be suitable for experienced engineer and can be used for determining the risks in a design or a process that use plasma. A physical experiment was conducted to demonstrate new features of plasma generation technology where results are compared with plasma simulation using Elmer FEM.

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1. Introduction and background

The design of plasma employing devices is a complex process demanding experience and skill that can be acquired with practice and time. The access to the laboratory equipment for prototyping of plasma devices can be expensive and hazardous to health, especially when the preliminary models are not sufficiently understood. It is possible to gain a perspective on the basic plasma physics by investigating the process specific parameters, although, it would be best to visualize any these behaviors in the process. Therefore, a multi-physics tool suitable for modeling plasma behavior would be beneficial to have a handle on the process parameters and variables. The training of engineers to familiarize with plasma processes is critical for achieving reasonable outputs from the plasma simulations, as would be the case for the engineers dealing with structural analysis, heat transfer, or computational fluid dynamics (CFD). Respectively, certain simulation tools are available commercially and the licensing for their use is available, other simulation tools are available as a result of the government research and made available to the public and academia under that government. The use of the government provided software is unlike the commercial software due to the level of detail and certain aspects of user interface. Elmer FEM is a hybrid case of a multi-physics software that was developed for the national CFD program by a chain of Finnish universities and in collaboration with engineering industries in 1997, and it was licensed under GNU public license in 2005 [1]. This software has a significant foundation that can be used in training of the aspiring plasma physicists and engineers if the case studies of plasma behaviors can be validated. Hence, the objective of finding and validating possible case studies was found worthwhile pursuing because it would allow for a wider range of interested engineers to gain experience in modeling plasma phenomena and allow to estimate the regions of risk and danger in the devices using plasma processes. Education and the access to the right tools can help in making designs that are safe and testing such tools is an essential step to validating their applicability [2,3].

The theory describing the flows interacting with the electromagnetic fields has been actively used for modeling liquid metals. The complex fluid behavior of plasma is unlike the metal flows due to its compressible properties and unique qualities of Coulomb interactions [4]. The foundational plasma research involved the plasma flow interactions with the electromagnetic fields, which lead to the culmination of fluid dynamics and electro-dynamic theories, generally confined to the study of Magneto-Hydro-Dynamics (MHD) [4].

The FEM discretization is based on a piecewise representation of the solution in terms of the basic functions [5]. The computational

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Nomenclature

Symbol	Definition		
B	magnetic field (T)	p	pressure (Pa)
E	electric field (V/m)	q_e	electron charge ($1.602 \cdot 10^{-19}$ C)
E	Energy (J)	t	time
h	Planck constant ($6.626 \cdot 10^{-34}$ J s)	T	temperature (K)
I	current (A)	T_e	electron temperature (K or eV)
J	current density (A/m^2)	$\boldsymbol{v}$	velocity of particle or fluid (m/s)
k_B	Boltzmann constant ($1.380 \cdot 10^{-23}$ J/K)	V	voltage (V)
m	total mass (kg)	$\eta_{opt\text{-}Air}$	Stoletov constant (81 eV/ion-electron pair)
$\dot{m}$	mass flow rate (kg/s)	Θ	heat flux (W/m^2)
M	molecular mass (kg/kmol)	μ	viscosity (Pa·s)
n	number of particles (electrons, ions per m^3)	σ_p	plasma conductivity (S/m)
		ρ	density (kg/m^3)

domain of the body of interest is divided up into smaller, finite element, domains and the solution in each element is constructed from the basic functions. The equations solved are typically obtained by restating the conservation equation in a weak form: the field variables are written in terms of the basic functions, the equation is multiplied by appropriate test functions, and then integrated over an element [5]. For Elmer FEM a system of multiphysics equations that encompass MHD phenomena can be obtained for plasma, and solved based on the initial and boundary conditions set into the simulation. The design safety can be achieved for the plasma devices by following through with a design approach outlined in the following flow chart, as shown in Fig. 1 [6].

The flow chart provides a process for the design approach with intrinsic focus on safety, where the design features are considered to be approached with an engineering design grounded in physical and safety foundations. This approach makes sense when the key tool for the design validation is tested. In present work, the first column of the chart is used in the method of approach, and the second and third column are used in the section on results and discussions respectively.

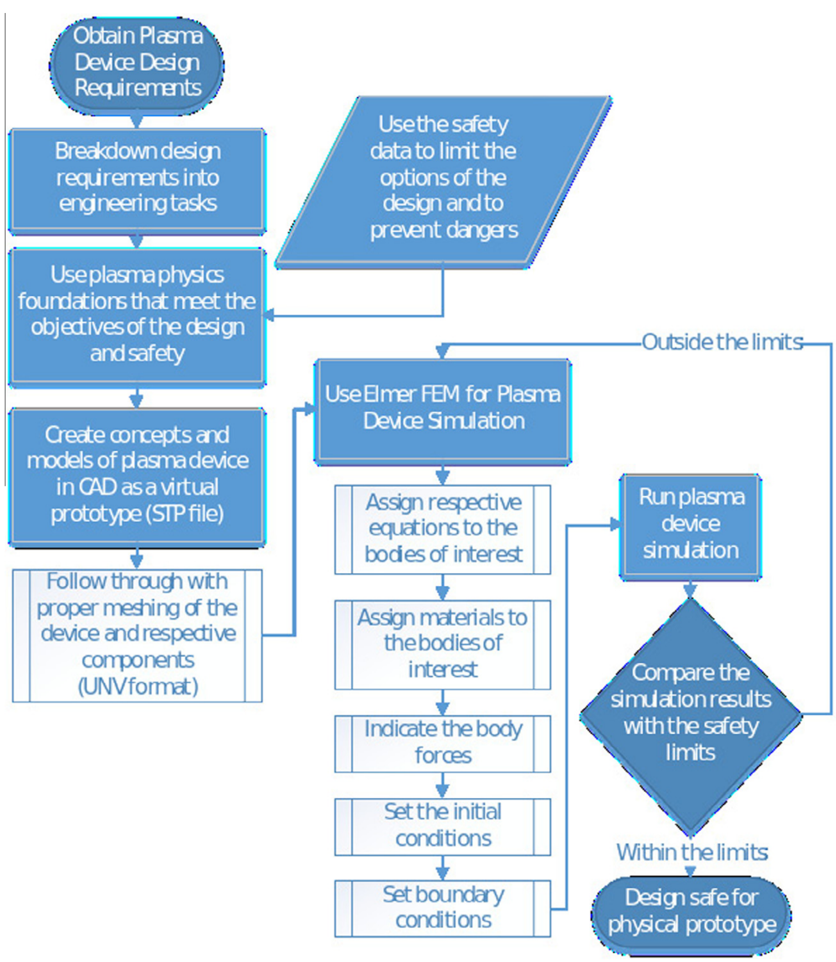

Fig. 1. Plasma device design flow-chart process using Elmer FEM [1].

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