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Thermal management of a notional all-electric ship electromagnetic launcher

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ABSTRACT

We present the development, coupling, and application of a quasi-3D multiphysics model of a notional all-electric ship electromagnetic launcher (EML) and a dynamic parallel-flow heat exchanger (PFHX) model to devise effective thermal management strategies for naval EMLs. The EML model combines a 2D electromagnetic-thermal model and a 3D thermal-fluid model developed based on the fundamental laws of electromagnetism, heat transfer, and fluid dynamics. Similarly, we applied the conservation laws to formulate a PFHX model and nondimensionalized it by identifying dimensionless parameters that pertained to the effectiveness-NTU method. We solved the coupled EML-PFHX model using finite element method and employed it to investigate the following aspects of naval EML thermal management: the effects of (1) thermal diffusion in the rail, (2) PFHX design and operation, and (3) cooling channel location on cooling performance and heat reversal. Subsequently, we deduced the following from our study: (1) thermal diffusion effectively assists the cooling channel with peak temperature reduction, and its contribution to the determination of optimal channel allocation is non-trivial; (2) improvement in cooling performance is not always directly proportional to larger heat exchanger size and higher flow rate—increased flow rate and NTU only result in higher pumping power as well as heat exchanger cost and volume without significant improvement in cooling performance beyond the optimal design and operating point; (3) placing the cooling channel close to the initial hot spot in the rail yields inferior cooling performance at high mass flow rate with 10 s of cooling and exacerbates the heat-reversal effect; and (4) optimal cooling channel allocation must therefore base on the given mass flow rate and cooling period—placing the channel near the initial hot spot is favorable for lower mass flow rates and shorter cooling periods, whereas channels should be placed at the rail center for equidistant heat flow from all four corners in the opposite case.

1. Introduction

Thermal management of electromagnetic launchers (EMLs) onboard all-electric ships poses critical challenges owing to their high heat dissipation rate and rapid transient, together with spatial and weight constraints imposed by ship structures. EMLs are high-power pulsating devices that accelerate projectiles by the interaction of an electric current and magnetic field, typically yielding velocities much higher than that achieved in conventional gas-driven launchers. Previous works have shown that it is possible to electromagnetically accelerate projectiles of a few kilograms to approximately 2 km/s or higher for ranges of 300–500 km [1–3].

The notional requirements imposed on EMLs by the U.S. Navy include a projectile mass of approximately 20 kg and a muzzle kinetic energy of 64 MJ [3,4]. In addition, EMLs are expected to launch 6–12 rounds per minute for long periods of time. The high current required to accomplish these goals, however, presents a set of challenges, including the excess heat and Lorentz force generated by Joule heating and high magnetic field, respectively, within a short time period, e.g., few milliseconds. From the thermal standpoint, stringent restriction on the cooling period as well as the intricate electromagnetic-thermal interactions in an EML make the design and analyses of its cooling systems more difficult.

Numerous theoretical and experimental studies have been conducted to devise effective cooling strategies for EMLs by characterizing their electromagnetic and thermal responses [4–22]. Previous works include the development of low-fidelity mathematical models [4,5,15,16] based on assumptions such as negligible current and magnetic field diffusion in 2D space, armature movement, or axial thermal diffusion (along the rail length). High-fidelity models [9,12,14,17–22], on the other hand, were devised in 3D space to accurately capture the complex physical interactions observed in an actual EML including the

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Nomenclature

A	area, m^2
$\mathbf{A}$	magnetic vector potential, $V\cdot s\cdot m^{-1}$
$\mathbf{B}$	magnetic field, T
c	specific heat, $J\cdot kg^{-1}\cdot K^{-1}$
C_r	ratio of heat capacity rate
d	diameter, m
$\mathbf{E}$	electric field, $V\cdot m^{-1}$
H	height, m
$\mathbf{H}$	magnetic field density, $A\cdot m^{-1}$
h	convective heat transfer coefficient, $W\cdot m^{-2}\cdot K^{-1}$; element size, m
I	electric current, A
$\mathbf{I}$	identify matrix
$\mathbf{J}$	current density, $A\cdot m^{-2}$
k	thermal conductivity, $W\cdot m^{-1}\cdot K^{-1}$; turbulent kinetic energy $J\cdot kg^{-1}$
L	length, m
m	mass, kg
$\dot{m}$	mass flow rate, $kg\cdot s^{-1}$
$\mathbf{n}$	normal vector
NTU	number of transfer units
Pr	Prandtl number
p	pressure, Pa
q	stability estimate derivative order
$\mathbf{q}$	heat flux, $W\cdot m^{-2}$
Re	Reynolds number
s	distance between two rails, m; scaling factor
T	temperature, K
$\widetilde{T}$	dimensionless temperature
t	time, s
$\widetilde{t}$	dimensionless time
U	mean velocity, $m\cdot s^{-1}$
$\widetilde{U}$	conductance ratio
$\mathbf{u}$	velocity vector, $m\cdot s^{-1}$
V	voltage, V; volume, m^3
$\widetilde{V}$	capacitance ratio
W	width, m
$\dot{W}$	power, W
$\widetilde{W}$	dimensionless power
x,y,z	Cartesian coordinates, m
$\widetilde{x}$	dimensionless length
$\dot{z}$	velocity, $m\cdot s^{-1}$
$\ddot{z}$	acceleration, $m\cdot s^{-2}$

Greek symbols

α	temperature coefficient of resistivity, K^{-1}
δ	penetration axis
δ^*	penetration depth, m
ε	turbulent dissipation rate, $W\cdot kg^{-1}$
σ	electrical conductivity, $S\cdot m^{-1}$
ς'	inductance per unit length, $H\cdot m^{-1}$
μ	dynamic viscosity, Pa·s
μ_r	relative permeability
μ_T	eddy viscosity, Pa·s
μ_0	vacuum permeability, $H\cdot m^{-1}$
ρ	density, $kg\cdot m^{-3}$
ϱ	resistivity, Ω·m; residual

Subscripts

ch	channel
fw	freshwater
hx	heat exchanger
i	inlet
max	maximum
min	minimum
o	outlet
p	pump
ref	reference
sw	seawater
T	turbulent
w	wall
0	initial

armature motion, but at a remarkably higher computational cost. Here we discuss a few representative works and identify the challenges persisting in modeling and simulation of EMLs.

Auton et al. [6] formulated a 2D EML model based on finite element method to quantize Joule heating in rails with arbitrary geometries and driving voltage waveforms. In [9], Liu presented a 3D EML cooling analysis for continuous shots with 20 s intervals, and concluded that heat reversal from coolant to rail will occur at the rear part of the rail if the coolant direction is from the breech towards the muzzle. Liu also reported that this phenomenon could be eliminated if the flow direction was reversed (from muzzle to breech) or if shorter cooling channels were used.

Hsieh [12] presented a Lagrangian formulation for a coupled structural, thermal, and electromagnetic diffusive process with moving conductors. The author solved quasi-static Maxwell's equations using a finite element analysis tool called Electro-Mechanical Analysis Program in Three Dimensions (EMAP3D). Fish et al. [13] also performed a 2D finite element analysis of multiple shots with and without cooling, while neglecting the heat diffusion along the rail length. The authors in [13] compared their simulation results against the experimental data for model validation.

More recently, the authors in [18–22] formulated 3D finite element EML models to study the effects of cooling channel design as well as contact resistance on peak temperature. In particular, Lin and Li [20] coupled the electromagnetic-thermal model to that of structural to investigate von Mises stress and the temperature of the armature as a function of space and time. Zhao et al. [18] verified the findings presented in [9] and demonstrated the importance of cooling channel location in the rail cross section in enhancing the overall EML cooling performance.

Based on our literature review, an "intermediate" multiphysics EML model is still needed to complement the computational advantage of low-fidelity models and accurate representation of multiphysics in 3D space achieved with high-fidelity models. Such a model allows for case studies, parametric analyses, and optimization to be conducted in a timely manner without the need for high performance computing. As part of the collective effort to develop computationally favorable EML models with sufficient accuracy, and to promote effective EML cooling strategies, we briefly introduced a quasi-3D multiphysics model of an EML onboard a notional all-electric ship in our previous work [23]. The proposed model combined a 2D electromagnetic-thermal diffusion model and a 3D thermal-fluid model formulated to describe the electromagnetic-thermal-fluid interactions in an EML during the launch and cooling period.

As a follow-up work, we discuss herein the details of the quasi-3D EML model summarized in [23] along with its enhancements, and extend our previous study to devise an effective thermal management strategy for naval EMLs. In particular, the enhanced EML model accounts for the nonuniform temperature distribution in all 3D space rather than in the rail cross section only; we achieved this by projecting