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Corresponding author: PUCCINELLI Elia
e-mail of corresponding author: elia.puccinelli@phd.unipi.it
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Title

Steady 1D Viscous Non-adiabatic Flow Model for the Determination of Inner Geometry and Power Density Profile of Nuclear Fuel Element

Authors

Elia PUCCINELLI [1], Angelo Pasini [2]*

** Corresponding author*
[1] Ph.D. Student, Department of Civil and Industrial Engineering, University of Pisa, elia.puccinelli@phd.unipi.it
[2] Assistant Professor, Department of Civil and Industrial Engineering, University of Pisa, angelo.pasini@unipi.it

Abstract

Nuclear rocket engines promise to boost manned and unmanned space exploration in the future decades, and there is a worldwide renewed interest in developing these propulsion systems thanks to their overwhelming performance. The layout of the most proposed configurations is very close to the one adopted during the NERVA project [1]: the reactor's core heats the propellant, which collects inside the thrust chamber and expands through a regeneratively cooled nozzle. Various fuel elements with several cylindrical coolant channels compose the reactor's core. The fluid passes through all of these channels subtracting heat from the nuclear fuel and using it to accelerate in the nozzle placed downstream of the fission reactor. This way, the propellant expansion, and thrust generation is governed by the gas dynamic acceleration as in chemical rockets. The present work represents the first step toward a new layout for this class of propulsion systems. The regenerative cooled nozzle is eliminated from the configuration and replaced with several smaller nozzles shaped inside each fuel element composing the reactor's core. The focus of this study is the determination of the optimum geometry of the channel of a general fuel element and the corresponding power density distribution. The flow inside the fuel element is viscous and non-adiabatic, and steady 1D generalized flow equations are applied. Initially, the isentropic case is studied. After fixing the required mass flow rate through the fuel element and the initial conditions, the variation in the axial direction of the Mach number along the channel mimics the distribution of the Mach number inside a bell-shape nozzle obtained by applying Rao's method [2]. A cylindrical surface approximates the outer surface of the fuel element, and the temperature profile along this surface constitutes another input for the problem. The fixed mass flow rate and Mach profile make the geometry of the channel depends on the flow stagnation temperature and pressure. The heat transfer in the equilibrium hypothesis between the fuel element walls and the fluid flowing through it gives a relation between the imposed temperature profile at the outer wall, the one at the inner wall, the power density, and the stagnation temperature. These relations allow obtaining a system of two ordinary differential equations in two unknowns: stagnation temperature and pressure. The equations of the non-isentropic case are solved numerically. The channel cross-section and the power density profile along the fuel element axis are estimated using the total pressure and temperature. The heat transfer equation involving the calculated power density and flow temperature provides the radial temperature distribution inside the fuel element at each cross-section.

References

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