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A new approach to nuclear reactor design optimization using genetic algorithms and regression analysis ☆

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ABSTRACT

A module based optimization method using genetic algorithms (GA), and multivariate regression analysis has been developed to optimize a set of parameters in the design of a nuclear reactor. GA simulates natural evolution to perform optimization, and is widely used in recent times by the scientific community. The GA fits a population of random solutions to the optimized solution of a specific problem. In this work, we have developed a genetic algorithm to determine the values for a set of nuclear reactor parameters to design a gas cooled fast breeder reactor core including a basis thermal–hydraulics analysis, and energy transfer. Multivariate regression is implemented using regression splines (RS). Reactor designs are usually complex and a simulation needs a significantly large amount of time to execute, hence the implementation of GA or any other global optimization techniques is not feasible, therefore we present a new method of using RS in conjunction with GA. Due to using RS, we do not necessarily need to run the neutronics simulation for all the inputs generated from the GA module rather, run the simulations for a predefined set of inputs, build a multivariate regression fit to the input and the output parameters, and then use this fit to predict the output parameters for the inputs generated by GA. The reactor parameters are given by the, radius of a fuel pin cell, isotopic enrichment of the fissile material in the fuel, mass flow rate of the coolant, and temperature of the coolant at the core inlet. And, the optimization objectives for the reactor core are, high breeding of U-233 and Pu-239 in desired power peaking limits, desired effective and infinite neutron multiplication factors, high fast fission factor, high thermal efficiency in the conversion from thermal energy to electrical energy using the Brayton cycle, and high fuel burn-up. It is to be noted that we have kept the total mass of the fuel as constant. In this work, we present a module based (modular) approach to perform the optimization wherein, we have defined the following modules: single fuel pin cell, whole core, thermal–hydraulics, and energy conversion. In each of the modules we have defined a specific set of parameters and optimization objectives. The GA system (GAS), and RS together, play the role of optimizing each of the individual modules, and integrating the modules to determine the final nuclear reactor core. However, implementation of GA could lead to a local minimum or a non-unique set of parameters, those meet the specific optimization objectives. The GA code is built using Java, neutronic analysis using MCNP6, thermal–hydraulics calculations using Java, and regression analysis using R.

1. Introduction

Genetic algorithms (GA) based optimization method has been successfully implemented in a wide range of engineering problems. However, very limited implementation of this method has been observed in nuclear engineering, specifically, nuclear reactor design. In this work, we have demonstrated a module based optimization method using GA, and implement this method in the design of a conceptual gas cooled fast breeder reactor. A module herein is a functionality or a physics based phenomenon that solves a specific problem. A module can be understood as a set of equations representing a physical phenomenon i.e. heat conduction, thermal hydraulics of a coolant across fuel pin cell through a reactor core, and neutron transport. In this work, we present a very generic solution approach where, different modules interact among each other and finally correspond with the GA

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structure (GAS) to optimize certain defined parameters and meet specific objectives.

A neutron transport and depletion code like MCNP, SERPENT takes a significantly long execution time if higher accuracy of results is desired. And, in a global optimization technique like GA, the code needs to be run for a significant number of input samples before a desired solution is obtained. Hence, we are using a spline based multivariate regression fit to perform predictive analysis. The regression fit is obtained from a set of trial data. Trial data is obtained when MCNP is run on a predetermined sample of input set, and the corresponding trial output parameters are obtained. The combination of the trial input set, and trial output parameters form the trial data. The trial data is obtained to build the regression fit. The regression fit is applied on the test data obtained from GA to determine the desired parameters in a satisfactory confidence level. It is to be noted that the output parameters for the test input is not obtained from the neutronics code, rather it is obtained from the regression fit.

A GAS is the central module that interacts with a specified set of the defined modules and performs optimization. The GAS is a combination of the GA optimization module and the regression model. The objective is to design a gas cooled fast breeder reactor core that can yield a, high neutron fast fission fraction (T_{ff}), high fuel burn-up (BU), high breeding ration (BR), and high thermal efficiency (η) using the Brayton cycle for energy conversion. It is to be noted that, material structural feasibility, transient analysis, safety analysis, probabilistic risk analysis, and economics are out of scope from this work.

We have defined the following modules those interact with the GAS for optimization. In the first module we determine the optimum r_F, and enrichment of U-233 in $(U-Th)O_2$ fuel to obtain the desired BU, infinite neutron multiplication factor (K_∞), and T_{ff}. In the second module we determine the BR, radial power peaking factor ($F_{PF,rad}$), axial power peaking factor ($F_{PF,ax}$), and effective neutron multiplication factor (K_{eff}). In the third module we perform a hot channel analysis to analyze the heat transfer across the fuel pin cell i.e. the flow of heat from fuel pin to the coolant wherein, we determine the optimum core inlet temperature, T_{in}, and, flow rate of the coolant (W) to determines the desired core outlet temperature, T_{out}, and temperature peaking factors. Finally, we determine the optimum T_{in}, and T_{out} to obtain a high thermal efficiency. A detailed description of the parameters and the optimization objectives of each of the mentioned modules is presented in a future section.

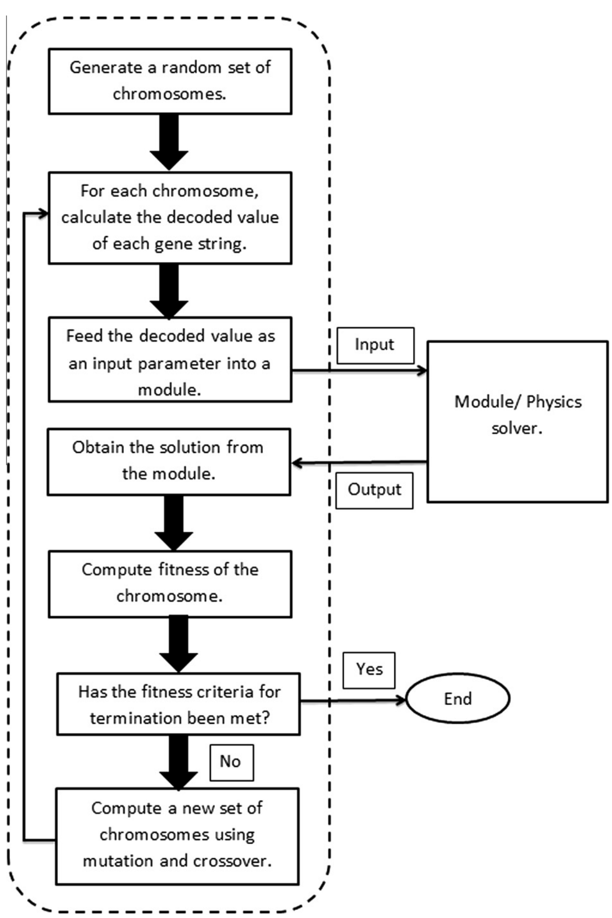

Fig. 1. Genetic algorithms flow chart.

1.1. Previous work

Previous work related to optimization, in problems related to nuclear engineering using GA includes, core design (Pereira and Lapa, 2003; Pereira et al., 1999; Haibach and Feltus, 1997), plant design (Cantoni et al., 2000), nuclear system availability and maintenance scheduling (Lapa et al., 2000; Marseguerra and Zio, 2000), fuel management (Chapota et al., 1999; Dechaine and Feltus, 1995), and spent fuel management (Omori et al., 1997). However, coupled neutronics-thermal hydraulics problems have not been explored and the effectiveness of GA in solving the coupled problems has not been evaluated. In all the above stated work, researchers have explored GA in solving single physics problems in nuclear engineering. However, in the current work, we present a module based approach to optimization in conjunction with multivariate regression and show that it is an effective tool in reactor core design in a multiple physics domain, where each physics domain is defined as a module.

In this work we have ignored the, safety aspects of a nuclear reactor, material and structural details, control elements including the control rods, fuel cycle, and economics of the nuclear reactor core design. A comparative analysis of different optimization methods is out of scope from this work. We have also ignored the analysis of different multivariate regression methods.

The remainder of this paper is organized as follows. First we introduce the underlying concept of genetic algorithms based optimization method, then we present our implementation method. Then, we present the motivation, and implementation details of the various modules used in optimization. Finally, we present the results and then conclude with a summary.

2. Genetic algorithms

GA is a search heuristic machine learning model which is derived from the process of natural selection based on the theory of species evolution (Darwin, 1859). It involves the processes, such as inheritance, reproduction, crossover, mutation, and others used for selection. Before we explain the implementation of GA in detail, it is very important to get the biological background of the concept. Every living organism consists of animal cells with, every cell consisting of a nucleus that has the genetic information of an organism. The DNA molecule in the nucleus consists of thread-like structures called chromosomes. The chromosome is a constitution of genes with, a gene located at specific locations called locus. A gene is the basic physical and functional unit consisting of instructions that define an organism i.e. how the organism survives, how it appears, and how it behaves in its environment. These characteristics determine the adaptability of the organism in the environment, also called as, the fitness of the organism. Basically, a gene encodes a trait of the organism, e.g. color of the skin.