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Multi-objective optimal design of vertical natural circulation steam generator

Lei Chen, Changqi Yan*, Jianjun Wang

National Defense Key Subject Laboratory for Nuclear Safety and Simulation Technology, Harbin Engineering University, 145 Nantong St., Harbin 150001, China

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ABSTRACT

In this work, a hybrid non-dominated sorting genetic algorithm was proposed and utilized to perform the multi-objective optimization design of a natural circulation steam generator, which included minimizing of the weight, the volume and the reactor coolant flow-rate. Sensitivity analysis of the design variables was carried out to study the relationships between the optimization variables and the objective functions, which was also helpful for the explanation of the optimization results. The mathematical model of the steam generator was validated by the RELAP5 code. The results show that the mathematical model has a good agreement with the RELAP5 model after modifying the boiling correlation in the secondary side; the proposed hybrid non-dominated sorting genetic algorithm is able to find much better spread of solutions and better convergence near the true Pareto optimal front compared to the non-dominated sorting genetic algorithm; reactor inlet temperature is the most important variable which influences the distribution of Pareto optimal solutions.

1. Introduction

Optimization methodology has been widely and successfully employed in the design of nuclear power plants, such as the reactor core (Pereira, 2004; Sacco, 2009), control system (Wagner et al., 2008; Claudio and Celso, 2003), refueling (Marcio and Roberto, 2011), etc. In recent years, that component size optimization is increasingly interested by many scholars, as difficulties are encountered in manufacture, transport and layout of large components of those nuclear plants with high power; besides, compact nuclear power plants are required in some special situations, such as the marine transportation, space station, etc.

Size reduction can be achieved by reasonable combination of the operation and structural parameters on the premise of satisfying design requirements and safety regulations. For single component, He et al. (2010) minimized the volume of a pressurizer by redesigning the system pressure, inlet and outlet temperatures of the core, inner diameter of the pressurizer, and the optimal capacity is 40.9% less than the original design; Qin et al. (2011a) optimized the system pressure, inlet and outlet temperatures of the core, outer diameter of the U-tube, tube pitch and coolant velocity in the U-tube in the weight optimization of a steam generator, and 17.16% weight reduction is achieved. For coupled components, Zheng et al. (2011) optimized the weight of a turbine unit by the complex-genetic algorithm. For the system, Qin et al. (2011b; 2011c) optimized the weight and volume of a reactor coolant system, respectively.

The prior works almost concentrated on a single objective, which may result in the optimization of the single objective and deterioration of other design focuses. Hence, multi objectives must be simultaneously considered in some means for an optimization work. In the multi-objective design of a steam generator, Chen et al. (1992) assigned weighting coefficient to each target, and then transformed the work to a single objective. However, the selection of weighting coefficient is heavily influenced by the designers' experience and preference. To get rid of such influences, the concept of the Pareto optimal solution is introduced in this work.

Goldberg (1989) firstly proposed the concept of the Pareto optimal solution and several algorithms were then developed (Srinivas and Deb, 1995; Osyczka and Kundu, 1995). However, the Pareto optimal solutions, obtained by the algorithms, are usually imprecise. One of the objectives of this work is to develop an effective algorithm.

An optimization work consists of three parts: (1) mathematical model of the problem studied, (2) constraints, (3) optimization algorithm. The model is the fundamental, which needs to be double checked. In this work, the authors attempted to validate the steam generator mathematical model (Liu et al., 2012) by the RELAP5 code.

* Corresponding author. Tel./fax: +86 0451 8256 9655.
E-mail addresses: changqi_yan@163.com, 312559511@qq.com (C. Yan).

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Nomenclature

Abbreviation

HNSGA	hybrid non-dominated sorting genetic algorithm
NSGA	non-dominated sorting genetic algorithm
MNSGA	NSGA with hyper-mutation strategy

General symbols

x	optimization variable vector
F(X)	objective functions
S	variable space
rnd	random number: 0 or 1
it	iteration step
dis	distance between two variables
x_s	son individual solution
x_p	parent individual solution
x_{new}	new individual produced by reflection or shrink manipulation
α	reflection coefficient
η	shrink coefficient
V_1	volume of the lower head (m^3)
V_2	volume of the lower shell (m^3)
V_3	conical shell volume (m^3)
V_4	volume of the upper shell (m^3)
V_5	volume of the upper head (m^3)
R_o	outer radius of the lower head (m)
D_L	inner diameter of lower shell (m)
t_L	thickness of the lower shell (m)
H_L	height of the lower shell (m)
D_H	inner diameter of the upper shell (m)
t_H	thickness of the upper shell (m)
ω	one-half the apex angle in conical sections
H_H	height of the upper shell (m)
D	inside length of the major axis of an ellipsoidal head
t_{UH}	thickness of upper head (m)
h	length of upper head straight edge (m)
V_{sg}	volume of steam generator (m^3)
m	mass flow-rate in the primary side of the steam generator (kg/s)
Pow	reactor power (kW)
T_{out}	reactor outlet temperature (°C)
T_{in}	reactor inlet temperature (°C)
C_P	specific heat at constant pressure (J/(kg °C))
P_1	primary system pressure (MPa)
d_o	U-tube outer diameter (m)
d_i	U-tube inner diameter (m)
s/d_o	ratio of U-tube pitch to U-tube outer diameter
v	average flow velocity in U-tube (m/s)
r_b	U-tube resistance (m^2*K/W)
r_f	fouling resistance (m^2*K/W)
λ	clad conductivity (W/(m*K))
K_1, K_2	scale factor
G_s	mass flow-rate of the steam (kg/s)
τ_1	integration time constant (s)

The objective of this study is to provide a new method in the multi-objective design of the steam generator. In Section 2, the concept of the multi-objective problem is introduced and a detail description of the hybrid non-dominated sorting genetic algorithm is presented; Section 3 is devoted to validate the mathematical model of the steam generator (Liu et al., 2012) by the RELAP5 code; a multi-objective optimal design of the steam generator is conducted in Section 4, and the results are discussed; finally, the conclusions of present work and suggestions for future work are presented in Section 5.

2. Hybrid non-dominated sorting genetic algorithm

Many real life optimization problems have several objectives. The objectives for a design problem will usually be conflicting. For example, a manufacture will have a requirement that the plant costs—construction, maintenance and running costs—must be as low as possible, and the plant life-span should be as long as possible. However, a cheap industrial plant will quite likely be short-lived. This is the domain of multi-objective optimization—how to weigh up conflicting objectives, which makes the multi-objective optimization much more different and difficult than the single-objective.

2.1. Multi-objective optimization problem and Pareto optimal solutions

A general multi-objective design problem can be expressed by Equations (1) and (2)

$$\min \ F(x) = [f_1(x),\ f_2(x), \ldots,\ f_k(x)] \quad s.t.\ x \in S \tag{1}$$

$$x = (x_1, x_2, \ldots, x_n)^T \tag{2}$$

Where $f_1(x), f_2(x), \ldots f_k(x)$ are the k objective functions, $(x_1, x_2, \ldots, x_n)$ are the n optimization variables, and $S \in R^n$ is the variable space. The multi-objective optimization is to minimize the vector F(x) by seeking out the best combination of the$(x_1, x_2, \ldots, x_n)$in the variable space.

However, for a general design problem, the objective functions are usually conflicting. Minimizing F(x) lacks clear meaning, as the set {F(x)} for all feasible x lacks a natural ordering, whenever F(x) is vector-valued. In order to determine whether F(x_1) is better thanF(x_2), and thereby order the set {F(x)}, the subjective judgment from a decision-maker is needed.

One property commonly considered as necessary for any candidate solution to the multi-objective problem is that the solution is not dominated. Considering a minimization problem and two solution vectors $x, y \in S$, x is said to dominatey, and denoted $x \succ y$, if:

$$\forall i \in \{1, 2, \ldots, k\} : f_i(x) \le f_i(y) \text{ and } \exists j \in \{1, 2, \ldots, k\} : f_j(x) < f_j(y) \tag{3}$$

All the non-dominated solutions (also named as "Pareto optimal solutions") constitute the Pareto optimal front. If the final solution is selected from the set of Pareto optimal solutions, there would not be any solutions that are better in all attributes. It is clear that any final design solution should preferably be a member of the Pareto optimal set. If the solution is not in the Pareto optimal set, it could be improved without degeneration in any of the objectives.

2.2. The non-dominated sorting genetic algorithm

Srinivas and Deb (1995) proposed the non-dominated sorting genetic algorithm (NSGA) to find the Pareto-optimal solutions. It is based on several layers of classifications of the individual solutions. The individual solutions are ranked on the basis of non-domination: all the Pareto optimal solutions are classified into one category and shared with the highest fitness value; then, this