REDUCED SCALE PWR PASSIVE SAFETY SYSTEM DESIGN BY PARTICLE SWARM OPTIMIZATION

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Abstract. *This paper presents an application of the particle swarm optimization technique (PSO) to a reduced scale design of a third generation PWR core, with single phase flow under natural circulation. Initially, this study aimed at analizing the robustness and consistensy of the technique for solving this class of problems. The PWR core, based on the LOFT TEST FACILITY, subject to this flow regime, has been used as a study case. The results obtained from the simulation were very promissing and thus they recommend the application of the PSO technique to real case thermohydraulic experiments of this nature, subject to constraints of physical, economical and operational nature.*

***Keywords**: Reduced Scale Experiments, Safety Passive System, Reactor Thermal-Hydraulics, Similarity, Particle Swarm Optimization.*

1. INTRODUCTION

Recent efforts on the development of advanced and innovative reactors deal with the incorporation of passive or intrinsic safety systems or features that do not require active controls or interventions in order to prevent accidents when malfunction events occur. These efforts are based on gravity, natural circulation or high temperature resistance.

There is already a good technical basis and a reasonable operational experience for the use of passive systems design in new reactors. In what concerns safety, the passive system system/component applications aims at simplifying safety systems and improve their reliability in order to reduce the effect of human actions and equipment malfunctions, as well as to give more time for the operators to prevent or attenuate the effects of severe accidents.

Due to the high cost of real-scale testing facilities construction, and also the impossibility of building them in some cases, reduced-scale facilities have been used for studying, understanding, and making predictions on systems that operate under natural circulation, for dynamical simulations may be performed on different flow types under different flow regimes. The development of these reduced-scale facilities is of utmost importance for supporting the prototype design, besides studying physical phenomena and also computer code validations. However, it is not an easy task to assure that a reduced-scale facility reproduces precisely the physical phenomena that occur in the prototype. It is quite a complex problem that involves a significant effort to perform a balance between the dimensionless numbers that represent the physical phenomena to be studied aiming at achieving the best combinations among structural parameters and operational conditions that lead to an optimal solution for the problem. The design of a reduced-scale facility must use a set of principles known as scale laws. These laws are the product of a dimensional analysis, which gives rise to the similarity relationships between the model and the prototype. In this sense, the facility allows for the dimensional modeling, that is, the performance of scale experiments in a replica called original construction model, which is named a prototype, with the purpose of projecting the obtained results from the model to the prototype.

Designing reduced scale thermal-hydraulic loops is a very important problem of nuclear engineering, and thus this work will focus on it. Unfortunately, establishing similarity conditions for a reduced scale loop which precisely represents the physical phenomena occurring in the prototype is an impossible task. It is well known that, if one uses the same material (fluid and structures) absolute similarity will occur only in a one to one scale, with operational conditions virtually identical to the ones of the real system (Ishii and Kataoka, 1984). To summarize, for a reduced scale system with the same materials as the prototype, absolute similarity and full simulation of all physical phenomena involved, will not be obtained. In this context, one should adopt the following strategy for a good reduced scale design: "give high priority to solutions with the best combinations of the experiment parameters more relevant to the phenomena under study, keeping in mind operational, physical and cost restrictions".

From Lapa *et al.*, (2004) we may corroborate that under the conditions above mentioned or even if other materials are under consideration, the design of a reduced scale loop is an optimization problem, which aims to determine the best combinations of structural parameters and operational conditions that yield the most adequate values for the dimensionless groups more relevant to the experiment being simulated. If one decides to use different materials he/she should then add to the optimization problem a discrete search for the physical characteristics more adequate to represent the phenomena occurring on different operational conditions of the reduced scale project.

In view of the above, this paper presents the application of a new methodology, that is, the formulation of a loop test section design as an optimization problem with constraints solved by PSO (Kennedy and Eberhart, 1995), and the analysis of thermal-hydraulic systems under natural convection. This new application is significantly more complex than analyzing forced convection systems, due to the coupling between the dynamical system (gravitational force and momentum) and the thermo dynamical systems (heat transfer processes) as it is impossible to solve for the speed distributions without taking into account the temperature corresponding distributions. The approach for this more complex situation is based on the intrinsic importance of the passive safety systems to nuclear engineering reactor applications and on the possibility of testing the performance of the methodology to solve strongly nonlinear optimization problems with search spaces having complex topological structures.

2. THEORETICAL FOUNDATIONS

2.1. Similarity

The design of large-scale equipment that involves fluid flows requires most of the time the construction of small models geometrically similar to the actual prototypes. However, this is not sufficient for the actual simulation of the involved physical phenomena. Besides the geometrical similarity, one must be sure that the model will behave like the prototype with time. According to the classical scale laws, the kinematical similarity assures that if the model and the prototype have the same speed scale factors, then the movement path and the particle speed ratios will also be similar. Although the geometrical and the kinematical similarities are necessary conditions for the experimental model to reproduce the flow in the prototype they are not sufficient. One can only conclude that the flow fields between both are similar when dynamical similarity also occurs, that is, when the force coefficients between both are equal. In short, dynamical and kinematical similarities are granted if the dimensionless number groups found have the same value both for the model and for the prototype.

2.2. The Optimization Problem

The optimization problem consists on approximating the significant non-dimensional groups through the search of the best operational and structural conditions characterizing a solution candidate, by using a weighted mean square method. The aim is to minimize the function *f* defined as:

$$f = \sqrt{\sum_{i=1}^{N_g} w_i \cdot \left[\frac{\left(G_i - \overline{G}_i \right)}{\overline{G}_i} \right]^2} \quad (1)$$

where, N_g is the number of significant dimensionless groups one intends to approximate, $\overline{G}_i$ is the expected value of a given dimensionless group; G_i is the value of a given dimensionless group corresponding to a specific design trial where there also intrinsically exist restrictions due to the allowable ranges of the design variables, and the w_i are normalized weights for the relative importance of each dimensionless group of the problem.

The optimization problem constraints consists of two classes. First, the solution candidates or reduced scale designs related to fluid boiling conditions should be discarded, since they represent a physical condition not being simulated. Second, the search variable of the problem (physical and structural conditions that compose the dimensionless groups) are searched among a restrictive range.

One can geometrically interpret the set of non-dimensional numbers as a search space with dimension N_g. In this space, the point of reference is defined by the coordinates of $\overline{G}_i$. So, the aim is to obtain the points G_i, which are as closer as possible to the $\overline{G}_i$, according to the chosen metrics. The present work employed the Euclidean norm and, as a consequence, one searches for solutions with the smallest values for (G_i - $\overline{G}_i$).

2.3. Particle Swarm Optimization (PSO)

Proposed by Kennedy and Eberhart, (1995), this method consists on the optimization of an objective function by means of the information change between a group of elements (particles), resulting in a non deterministic, efficient, and robust optimization algorithm that can be easily implemented in a computer. As an analogy between the social behavior of groups and the optimization algorithm, the space where the groups move through corresponds to the problem search space and the point where the nest or food is corresponds to the optimal solution, that is, the maximum or minimum of a given objective function. In this sense, the particle swarm is identical to other methods of evolutionary computation in which a population (swarm), made up by individuals (particles) scans the space in order to find an appropriate solution for a given problem. However, in the particle swarm optimization, each individual has a speed, which is responsible for the space exploration (evolution) and a memory, to retain the best position already visited, Eberhart *et al.* (1996). The algorithm also considers the best position found by the population.

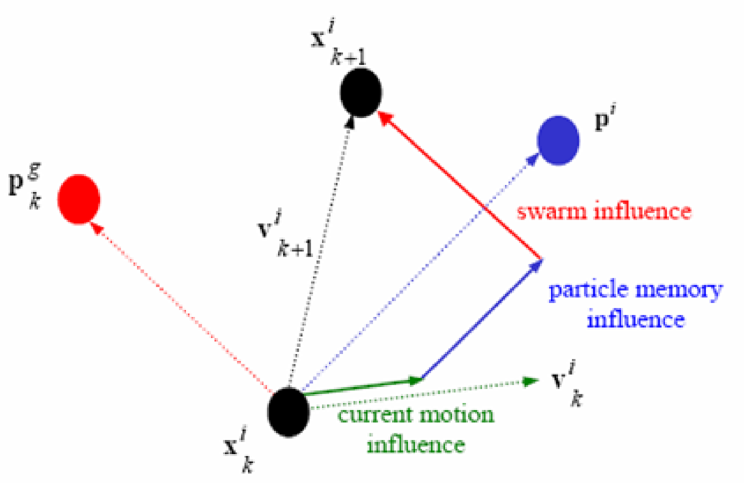

Figure 1: Description of the speed and position updating in the PSO. Source: Hassan *et al.*, 2004.

3. METHODOLOGY

The methodology proposed in this paper is based on the pioneering research developed in the reduced scale systems project through advanced optimization techniques, Lapa *et al.* (2004), and can be summarized as follows: 1. Definition of the adequate physical model for the problem to be analyzed; 2. Dimensioning of the physical model and determination of the relevant dimensionless groups; 3. Formulation of the optimization problem with constraints: to design a testing section that takes into account the same dimensionless numbers of the original phenomenon, but with design parameters that are constrained by economical, constructive, or operational considerations; 4. Use of the PSO to solve the optimization problem; 5. Critical revision of the solution found by an expert, returning back to step 3, if necessary.

3.1. Dimensioning the physical model

A thermo-hydraulic circuit of a PWR under a natural circulation regime was modeled by using the continuity and momentum equations, two energy equations and a one-dimensional boundary condition around the circuit composed by many sections (Ishii and Kataoka, 1984).

A steady state fluid flow was considered with the following assumptions: the viscous dissipation effects and the axial condition are negligible; heat losses are negligible; for a single phase liquid flow, the fluid is assumed to be uncompressible, so that the Boussinesq approximation is valid. As a result of this latter, the fluid properties may be considered constant in the conservation equations, except for the density in the buoyancy force term, which is assumed to vary linearly with temperature.

After the analysis of the group dimensions, a minimal set of six dimensionless groups was found (Richardson, Friction, Modified Stanton, Thermal Length Ratio, Flow Area Ratio, and Conduction Depth Ratio), which are significant for the transfer characteristics of momentum, mass and energy for a single phase flow under natural circulation (Cunha, 2004).

4. CASE STUDY

Due to the complexity of the problem at hand and the lack of knowledge concerning the search space and the physical, financial, and operational constraints, it turned out that the evaluation of the methodology proposed in this paper needed to be evaluated by means of simulations performed on a problem whose solution was known a priori (global optimum value). The LOFT facility (Reeder, 1978) was then chosen, and so the representative dimensionless numbers of the physical phenomena could be calculated for comparison purposes.

The search parameters for the project under natural circulation and with a nominal power removal capacity of one percent are shown in Table 1. These physical variables, chosen as search parameters, were directly or indirectly sufficient for the calculation of all needed dimensionless numbers.

Table 1: Search parameters

Search parameters	Specification
ΔH	Height between thermal centers
d	Rod external diameter
q_0	Rod power
p_0	Operation pressure
l_0	Rod active length

The condition supplied for the PSO to perform the search in each simulation established intervals with a range of 50% over and under the global optimum values for each variable, as shown in Table 2.

Table 2: Search intervals for the design parameters

Search variables	Global optimum value	Search interval	
		Minimal	Maximum
ΔH (m)	4.67250	2.46500	7.39500
d (m)	0.01070	0.00535	0.01605
q_0 (w)	1.55000	1.10000	1.70000
p_0 (MPa)	3.90000	1.95000	5.85000
l_0 (m)	1.68000	0.84000	2.52000

To make the proposed strategy viable many simulations were performed taking into account not only the distinct operational conditions but also many randomization seeds, that is, different initial conditions for each configuration considered.

Due to the difficulties imposed by the search space, it was settled that the PDO would virtually reach the global optimum solution as long as its results fulfilled a tolerance criterion of 2.5% around the global optimum solution, although a criterion of 5% was also considered. Among the different configurations considered, it was verified that configuration 1 consistently reached the global optimum solution in 30.44% and 20.29% of the time, with the given tolerances, respectively, while the remaining configurations presented the following results: 29.71% and 10.15% for configuration 2, 26.09% and 13.04% for configuration 3, and finally 27.27% and 17.05% for configuration 4, as shown in Table 3.

Table 3: PSO Operational conditions for the best configurations

Operational conditions	Config . 1	Config . 2	Config . 3	Config . 4
Objective: PSO [0]= min or [1]=max	0	0	0	0
PSO (Random seed)	-	-	-	-
PSO C1 (constant)	3.0	2.5	1.4	4.0
PSO C2 (constant)	1.0	1.5	1.4	1.0
Number of cycles (≤ 100)	100	100	100	100
Number of iterations	2500	2500	2500	2500
Stopping condition (Num Iter.%)	12	12	12	12
Aprox mode ([0]=Lin=[1]=Log=[2]=Exp)	0	0	0	0
Number of particles (≤ 100)	500	500	500	500
Initial weight (partícles)	0.8	0.8	0.8	0.8
Final weight (particles)	0.1	0.1	0.1	0.1
Mult. Factor (Dw=1, 2, 3, 4, 5)	2	2	2	2
Part. Inertia ([0]=general [1]=ind.)	0	0	0	0
Inertia factor (individ. (%))	1	1	1	1
Particle maximum speed ([0]=auto)	0.9	0.9	0.9	0.9
Number of dimensions (≤ 20)	8	8	8	8

The PSO obtained much the same solutions as the LOFT-based ones. Among these, the best representative ones were chosen, with very good characteristics that demonstrate the methodology capacity for obtaining the operational conditions for the LOFT facility, that is, the global optimum value, as demonstrated in Table 4.

Table 4: Design parameters and reference dimensionless numbers for the best case study simulations

Search parameters and dimensionless numbers	Global optimal value	Simulation 1 18041981	Simulation 2 4071948	Simulation 3 19071954
ΔH (m)	4.6725	4.6670	4.6700	4.6699
d (m)	0.0107	0.0107	0.0107	0.0107
q_0 (w)	1.5500	1.5472	1.5539	1.5453
p_0 (MPa) (E1)	3.9000	3.8921	3.9111	3.8867
l_0 (m) (E2)	1.6800	1.6799	1.6800	1.6799
Richardson (E-2)	2.0810	2.0841	2.0842	2.0842
Stanton(E-2)	8.5036	8.5041	8.5040	8.5040
Friction(E2)	3.5163	3.5163	3.5163	3.5163
Thermal Length Ratio	2.7812	2.7798	2.7798	2.7798
Conduciton Depth Ratio	1.6061	1.6061	1.6061	1.6061
Flow Área Ratio	1.0000	1.0000	1.0000	1.0000
Fitness (E-6)	ZERO	0.9910	1.3074	1.4018

The simulations analysis' main focus was the representative dimensionless numbers of the physical phenomena related to the thermo-hydraulic experiment obtained in the three simulations. By comparing them to the reference values, one will notice that they are very small.

For simulations 1 to 3, the Richardson number errors were .148%, .153%, and .153%, respectively. For the Stanton number, the errors were all equal to .005%. For the Friction number, they were equal to .0003%, .0009%, and .0009%, respectively. In what concerns the Thermal Length Relation number, the errors obtained were all equal to 0.0536%. The error for the Conduction Depth Ratio number was noticed only for the third simulation, and it was equal to .00006%.

5. CONCLUSIONS

The performance of the dimensionless numbers shows that all simulations performed are excellent quality designs. All of them were able to represent the physical phenomena of the actual design with very low levels of distortion. Another conclusion is related to the design parameter comparison. All simulations presented design parameters which were slightly different from the reference value, but all of them led to very good results.

Due to the very good performance obtained, this study was able to allow for the analysis of the PSO performance in a reduced scale experiment, where the new simulations to be performed will undergo economical, physical, and operational constraints, which will certainly influence the search intervals of some design variables, thus enhancing the degree of difficulty for the computer software to perform the design parameter adjustment and lead to the best adjusted dimensionless numbers that represent the physical phenomena to be simulated.

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