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TECHNO-ECONOMIC OPTIMIZATION OF THERMOSSYPHON HEAT EXCHANGERS DESIGN USING MATHEMATICAL PROGRAMMING

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ABSTRACT

An Optimal Synthesis program for designing Heat Pipe Heat Exchangers (HPHE) is developed in this work. The program is the union of a simulation model, mainly based on Heat Transfer and Fluid Flow empirical correlations for thermosyphons, and an optimization procedure based on Evolutionary Algorithms. The simulation model was implemented on an Excel® spreadsheet, with aid of Visual Basic for Applications® programming. The chosen optimization method procedure was a Genetic Algorithm. Several shapes and arrangements of two-phase thermosyphons can be considered to attend one single thermal load. The objective of this work is to prescribe the cheaper design configuration among all chosen possibilities. Using the proposed optimization program, a case study is performed regarding the design of a heat recovery heat exchanger for a small gas turbine. The purpose of the equipment is to recover heat from the turbine flue gases for thermally driving an air conditioning absorption chiller. The use of an evolutionary optimization technique allows the program to deal with discrete variables, such as a given set of tube diameters that are commercially available. Using a small number of design variables, a comparison between exhaustive simulation and the optimization program is done. The proposed technique has found the optimum solution with a very few computational effort. It is physically impracticable to execute an exhaustive simulation for comparisons, employing a larger number of design variables, Even thugh, the optimization program showed itself a useful design tool.

KEY WORDS: Evolutionary algorithms, thermal design, mathematical programming

1. INTRODUCTION

Brazilian industries have a growing interest in thermosyphon heat exchangers because of their good performance, reliability and lifetime.

Proper thermal design of a Heat Pipe Heat Exchanger (HPHE) is essential to ensure economic viability. Poor design can lead to oversized or subsized equipments. Sometimes a technically adequated thermal design can be improved by means of finding a cheaper design solution that fits to the same thermal load. Nowadays, when industry is considering applying this new heat exchanger technology, the decision is quite often an engineering-economy analysis of a traditional heat exchanger substitution. A techno-economic design tool can be decisive in this process.

Nowadays, the literature recognizes the importance of a multi-parameter model for the design of HPHEs. Silverstein (1992) proposes a simplified design method where the set of design parameters is modified manually and the interdependent variables are recalculated in an iterative process until a technically satisfactory solution is found. In a review of HPHE design optimization Faghri (1995) found only multivariable design simulation models, one of them coupled to an orthogonal regressional analysis method for post-optimization.

Mathematical programming is proposed in this work for prescribing optimal HPHE design solutions. In the proposed approach, HPHE simulation is treated as a black box by the optimization routine. The simulation models evaluate the HPHE cost for each configuration proposed. The cost is dependent of the HPHE physical performance. The cost function can be non-linear, non-smooth or even function of discrete variables, such as a given set of commercially available tube diameters. The optimization routine will change the set of design variables until an optimum criteria is achieved. By splitting simulation and optimization routines, each model can be improved individually. The Figure 01 shows a diagram of the optimal synthesis process.

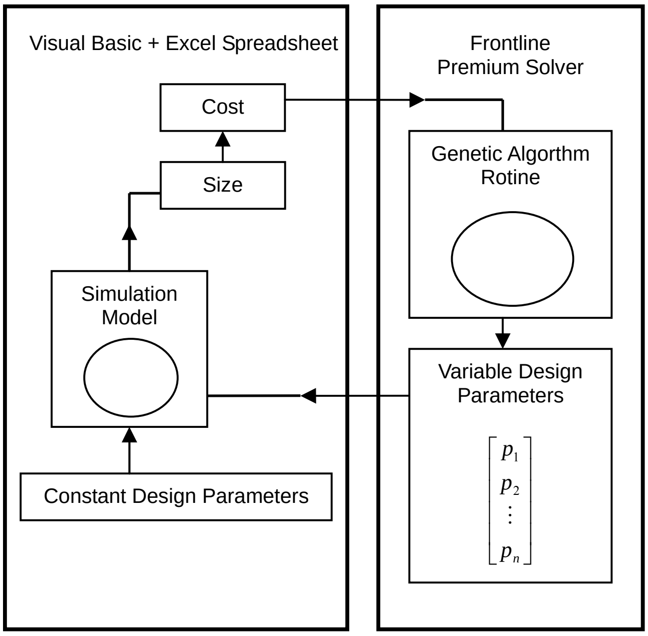

Figure 01. Diagram of Optimal synthesis process.

The objective can only find the cheaper equipment with respect to its acquisition price. The objective can be also to find the cheaper equipment upon a Life Cycle Cost Analysis that takes into account the manufacturing and operational costs along its life cycle. The annual life cycle cost can be evaluated by means of an Engineering-Economy discounted sum of all expenses during the life cycle.

2. THE HEAT EXCHANGER SIMULATION MODEL – TROCATER II

TROCATER II is a simulation program developed for thermal design of thermosyphon heat exchangers. It is mainly based on empirical correlations for calculating external and internal thermal resistances in a thermosyphon tube bundle.

The input data are: mass flow rate of the hot and cold streams; inlet and outlet temperatures of the hot stream; inlet temperature of the cold stream; hot and cold stream composition (among water, air and combustion gases); tube length; evaporator/ condenser aspect ratio; tube diameter; tube wall thickness; tube material; fin height; fin pitch; fin thickness; tube bundle arrangement; tube spacing and number of tubes in each row.

The outputs are number of tubes in the heat exchanger bundle; weight of the heat exchanger, pressure loss, maximum velocities and Reynolds number on cold and hot streams; thermal resistances evaluation and tests of limits of operation for thermosyphons.

The first step is to calculate mass and energy balance using the input data. In the TROCATER program itself, there are tables and functions implemented for the evaluation of physical properties of hot and cold streams and of the working fluid.

Using the ε-NUT method, the program calculates the thermal conductance of the entire Heat Exchanger. After that, empirical correlations, obtained from thermosyphon literature, are used for the evaluation of the internal thermal resistances of each thermosyphon. Once the total thermal resistance of each thermosyphon is evaluated, the number of thermosyphons can also be evaluated.

This process is iterative. The main iteration loop is the calculation of number of tubes, which is dependent of the total thermal resistance of each tube. The external thermal resistance of each tube is also dependent of the number of tubes. Another important loop is for the calculation of working fluid temperature, which is interdependent of the thermal resistances of each tube.

3. THE OPTIMIZATION ROUTINE – GENETIC ALGORITHM

Genetic Algorithms is a popular method for avoiding local optima. It follows the process of biological evolution to find better and better solutions. The only way to prove that a given genetic algorithm leads to a global solution is to evaluate all the entire dominium of the objective function.

In a genetic algorithm, the vector of variable design parameters – called decision variables – for the objective function is treated like a gene. The method evolves good heuristic optima by operations combining members of an improving population of individual solutions. The best single solution so far will always be part of population, but each generation will also include a spectrum of other solutions. From generation to generation, new solutions are created by combining pairs of individuals in the population. This kind of ‘reproduction’ occurs among elite individuals. Other kind of new individuals are produced from randomic mutation of individuals from the last generation. A given amount of elite individuals are preserved to the next generation. More details of genetic algorithms can be found from Rardin (1998).

In this work, a commercial implementation of the genetic algorithm routine called Premium Solver from Frontline Systems was used. This package is an add-on to MS-excel spreadsheet.

3. PROPOSED CASE STUDY

The case study chosen was the design of a Heat Recovery system for a small gas turbine, installed at CENPES, the research center of PETROBRAS, the Brazilian state oil company. The objective is to use the flue gases heat of a Capstone C60 gas turbine to heat water for thermally drive a Yazaki absorption chiller, for air conditioning purposes. In the existent experimental rig, there is a conventional shell-and-tube heat exchanger. The Figure 02 is a schematically diagram of the installation.

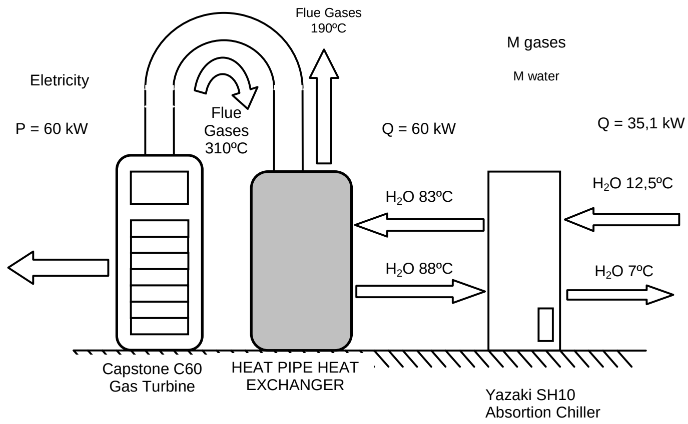

Figure 02. Schematically diagram of the installation.

The flue gases temperature at the turbine outlet can reach 350 °C at atmospheric pressure. The absorption Chiller used has a power of 35.14 kW. This model has a normal rated power of approximately 60 KW. The mass flow rate from the gas turbine is 0.49 kg/s.

The mechanical design concept for the HPHE involves the use of a pair of cubic shaped thermosyphon bundles. The equipment shell will be also cubic, and the best bundle geometry (aligned or staggered at 30°, 45° or 60°) will depend of the results of thermal design that will be described in this work.

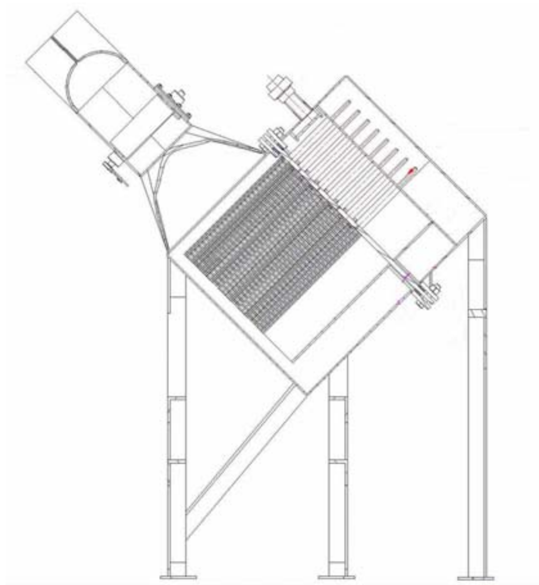

Figure 03. Mechanical design concept of the HPHE.

The maximum geometric dimensions of the developed equipment are width: 88.265cm; height 178.28 cm and lenght 123.19 cm.

4. RESULTS

The decision variables chosen for the optimization process of the HPHE were tube length; evaporator / condenser aspect ratio; tube diameter; fin height; fin pitch; fin thickness; tube bundle arrangement and tube spacing.

In a first step, a discrete set of values was chosen for each decision variable, as presented on Table 01. Variables P_1 to P_5 are continuous, and Variables P_6 to P_8 are considered discrete, since they were extracted from a list of commercially available sizes of finned tubes.

Table 01. Decision variables (DNA) chosen for the case study.

	Index					Unit
	1	2	3	4	5	
P_1- Heat Pipe aspect ratio	70	80				%
P_2- Tube Spacing	1,75	2,00	2,25	2,50	2,75	[mm]
P_3-Fin relative Height	0,25	0,50	1,00			%
P_4-Tube Leght	0,5	0,75	1,00			[m]
P_5-Fin pitch	0,003	0,005	0,008			[m]
P_6-Bundle arrangement	30	45	60	90		[°]
P_7-External Diameter	12,70	19,05	25,40	38,10		[mm]
P_8-Fin Thickness	0,001	0,0015	0,002			[m]

A unique design configuration can be expressed by means of a vector containing indexes of design parameters called *DNA.* For example: the DNA $[2,1,3,1,1,1,1,1]^T$ represents a design configuration were P_1=80%, P_2=1,75, P_3=1,00 and so on. Each design configuration will be further called *individual.*

4.1 Exhaustive Simulation

In a first step, all design scenarios were generated by an exhaustive procedure implemented in Visual Basic for Applications. This procedure generates the design results for all combination of parameters. The total population of individuals to be generated is 2x5x3x3x3x3x4x4x3=12960. As mentioned previously, the TROCATER II model performs some tests for limits of thermosyphon operation. Any individual that presented this limitations were considered non-feasible solutions, and were discarded.

The exhaustive simulation run took 42 hours of computational work on a PC compatible machine with a 3 GHz CPU. An amount of 4320 individuals were considered feasible among the 12960 cases.

The objective of this work is to prescribe the cheaper design configuration among all chosen possibilities. It is know that exist a straight relation between numbers of thermosyphons, weight of equipment and the price of the design configuration. In order to visualize low price individuals, the results were plot in a population graph of number of thermosyphons versus weight of the equipment (Figure 04)

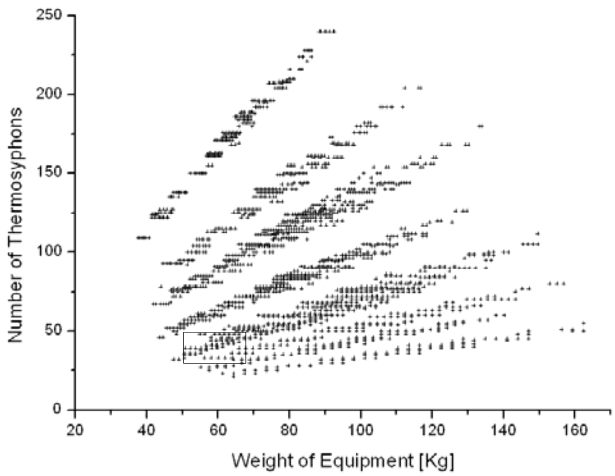

Figure 04. Population distribution of configurations.

Each point on Figure 04 can refer to more than one individual, since some exact superposition was noticed. There are 4320 individuals in this space.

Some cheaper individuals highlighted inside the rectangle in Figure 04 were plotted in Figure 05. These individuals have low number of thermosyphons and low equipment weight. A detailed description of this individuals (identified by numeric labels) can be found on Table 02 presented further in this work.

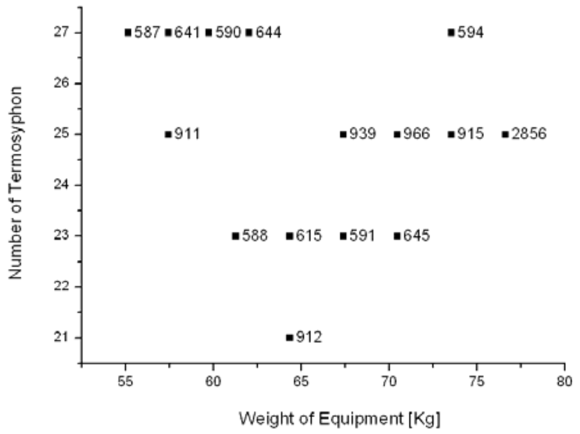

Figure 05. Best individuals found on

For the optimization process, the equipment price was chosen as the objective to be minimized. In the absence of a detailed survey for the price function, a simple function of number of tubes and equipment mass was developed with basis on 3 surveys for HPHEs from 700 to 7000 kW. The objective function is:

$$P = W \times 2.415 + N \times 273.421 + 136356.27 \qquad (1)$$

Where:

P equipment price [US$];
W equipment weight [kg];
N number of thermosyphons.

The objective function was applied to the feasible population, and the best individuals were presented on table 02.

Table 02. Best individual cases

	Aspect ratio	Tube Spacing	External Diameter	Fin Thickness	Fin relative Height	Fin pitch	Tube Leght	Bundle arrangement	Total Weight	Numbers of Tubes		Heat exchanger Total Leght	Price Function
	index	index	index	Index	Index	index	index	Index	kg		mmH_2O	m	kUS$
912	1	3	4	1	1	1	3	3	64	21	46	0,16	142,2
588	1	2	4	1	1	1	3	3	61	23	73	0,11	142,8
615	1	2	4	2	1	1	3	3	64	23	72	0,12	142,8
642	1	2	4	3	1	1	3	3	64	23	71	0,12	142,8
2208	2	2	4	1	1	1	3	3	64	23	60	0,12	142,8
591	1	2	4	1	1	2	3	3	67	23	69	0,12	142,8
618	1	2	4	2	1	2	3	3	67	23	68	0,12	142,8
1560	1	5	4	1	1	1	3	3	67	23	34	0,27	142,8
1587	1	5	4	2	1	1	3	3	67	23	33	0,27	142,8
2235	2	2	4	2	1	1	3	3	67	23	59	0,12	142,8
645	1	2	4	3	1	2	3	3	71	23	67	0,13	142,8
1614	1	5	4	3	1	1	3	3	71	23	32	0,28	142,8
2211	2	2	4	1	1	2	3	3	71	23	56	0,13	142,8
2238	2	2	4	2	1	2	3	3	71	23	56	0,13	142,8
2262	2	2	4	3	1	1	3	3	71	23	58	0,13	142,8
3180	2	5	4	1	1	1	3	3	71	23	29	0,28	142,8
3207	2	5	4	2	1	1	3	3	71	23	28	0,29	142,8
911	1	3	4	1	1	1	2	3	58	25	91	0,19	143,3
939	1	3	4	2	1	1	3	3	67	25	45	0,17	143,4
966	1	3	4	3	1	1	3	3	71	25	45	0,17	143,4

The prices for the best individuals are very close. The 20th individual in the ranking is just 0,8% more expensive than the leading individual. Indeed, there is a narrow range of number of tubes (21 to 25) and a narrow range of equipment weight (61 to 71) among the 20th leading individuals.

The price of a small heat pipe exchanger is more sensible to a change in the number of tubes then an increase of weight. The increase in price per number of tubes is proportional to manufacturing operations (drilling, welding, etc) and to men hours of work. As a consequence, the individuals with better performance have a few numbers of tubes, large tube length, large tube diameter, and a 60° bundle arrangement.

4.3 Optimal Synthesis

A genetic algorithm routine was used to find the best individual instead of the exhaustive simulation procedure. The number of individuals chosen was 100, which follow the recommendation of at least 10 times the number of decision variables. The mutation rate chosen for each generation was 7.5% in each generation. The optimum point reached was the individual 912, represented by the DNA $[1,3,4,1,1,1,3,3]^T$. It is the individual that is in the top of the ranking of exhaustive simulation cases.

The optimization run took 5 hours of computational work in the same computer used for the exhaustive procedure (Fig 06). Therefore, the optimization process was 8.4 times faster than the exhaustive process. With the increase of the number of decision variables, an exponential growth of the time of exhaustive simulation is expected. In contrast, the time increases is linear for genetic algorithms.

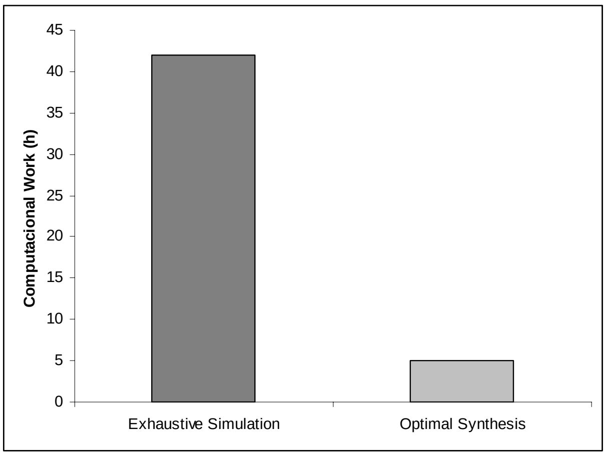

Figure 06. Comparison of computational work between exhaustive and genetic algorithms

CONCLUSION

The optimal Synthesis program developed in this work showed itself very useful in the design of Heat Pipe Heat Exchangers (HPHEs). Once an objective function is established, the optimum design can be found with a very few computational effort in comparison with parametric analysis and exhaustive procedures. Multi-parameter optimization techniques are particularly useful when the designer is dealing with a new application of HPHEs.

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