OPTIMIZATION OF FURNACE LATERAL SUPPORTS THROUGH GENETIC ALGORITHMS

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Abstract. *Optimization of mechanical components is an important aspect of the engineering process; a well designed system will lead to money saving during the production phase and better machine life. Moreover, optimization actions will increase the engineering investment. Since computer time is inexpensive comparing to production, an efficient design tool was made to carry out this task: an optimization model based on genetic algorithms. This computational tool is employed specifically for the analysis and design of a lateral tube support of a cabin heater with horizontal tube coil of Petrobras' refinery. An important information is that 40% of the unscheduled stops in this kind of fired heater are related to the tube support systems, which shows the relevance of those components. The developed numerical tool is capable of selecting the set of design variables that satisfies the structure safety requirements while achieving a minimum structure weight and consequently minimum cost. The serviceability and strength requirements are considered in the design problem as specified in API560. The optimum design algorithm takes into account the linear response of the lateral tube support due to the effect of dead load stress and dead load plus frictional stress. The loads are caused by the tubes inside the fired heater. The results show that the model convergs to a very efficient solution without any engineer intervention. A real example is included to demonstrate the efficiency of the algorithm.*

Keywords: *genetic algorithms, tube supports, fired heaters, mechanical design*

1. INTRODUCTION

The furnace shown in Fig. 1 is used in oil refinery to heat the fluid for fractional distillation columns. The furnace heats the crude fluid which passes through a distillation tower, where some oil products such as gasoline and diesel oil can be obtained. The design of this industrial furnace is complex and involves several systems. Some of those systems are the internal components which are submitted to high temperatures. An important internal component is the system that gives support to the tube coil. The tubes are supported in two sections: radiation and convection.

Figure 1. Cabin Heater.

In the radiation zone, which is so called because the main heat exchange mechanism is radiation, the tubes are supported near the furnace wall. This type of support is lateral and localized in the radiation zone of the furnace. Around 40% of the unplanned furnace shutdowns are caused by failures of the tube support system. Besides, those supports are manufactured with expensive materials. The design of a support considering some in service safety aspects and its minimum weight will allow a significant cost reduction.

The design of the lateral supports of the radiation zone of Petrobras heaters have been done using the FurnaceLSupport program which was developed by the company technicians. This program considers stresses caused by the weight of the tubes associated with long-term stresses and stresses caused by tube expansion, associated with short-term stresses. This program is based in the API 560 code (API STANDARD 560, 2001), specific for industrial furnaces. This code covers recommendations and procedures for the design of the tube supports running inside the heater, considering that the supports work under severe creep regime. This code also establishes that the supports shall be designed considering two types of loads: long-term (tube weights) and short-term (tube weights + friction caused by the temporary expansion of the supported tubes).

The optimization of the lateral supports requires many simulations with several design variables which turns it an exhaustive and expensive task. Classical optimization approaches involves gradient information that can be difficult to apply to most of the real-world engineering optimization problems. In recent studies, some other problems were addressed using Evolutionary Algorithms. In those studies the optimization of a mechanical design considering a particular component such as a turbine (Corriveau *et al.*, 2009), a dome (Kameshki and Saka, 2006) or a conical tank (ElAnsary *et al.*, 2009) was efficiently performed. Thus, Evolutionary Algorithms such as Genetic Algorithms can be an interesting alternative to solve those problems that gradient-type optimizers have failed to meet. The results obtained with the optimization algorithm, especially developed for this study, were compared with the design of a real furnace of Petrobras REPAR (Paraná Refinery). These refinery furnaces supports were designed employing the FurnaceLSupport. The material used to manufacture the support of the F-2102 A/B Furnace of REPAR (Atmospheric Distillation) is identified as: ASTM A297, HP Grade (25Cr-35Ni+Nb).

This optimization approach for the design of the lateral supports of refinery furnaces, using Genetic Algorithms, has shown great improvements in the supports. The search of the configuration with the best geometrical parameters allowed an increase in the mechanical resistance and a reduction in the weight. A reduction of the support weight, which will be addressed in this study, ensured a cost reduction in the manufacture stage, which may be significant if we consider that REPAR furnaces included 640 (six hundred and forty) of such cast tube supports.

2. DEFINITION OF THE FURNACE SUPPORT VARIABLES

The supports of the heater tubes have some distinct characteristics and are divided into three separate items: radiation supports, convection intermediate supports (tubesheet) and convection end supports. This study addresses the radiation supports. Such supports may adopt various geometries, depending on the position of the tube inside the furnace. When the tubes run horizontally, tangent to the furnace wall, a lateral support is used. A possible geometry for the lateral support of furnaces is shown in Fig. 2 below.

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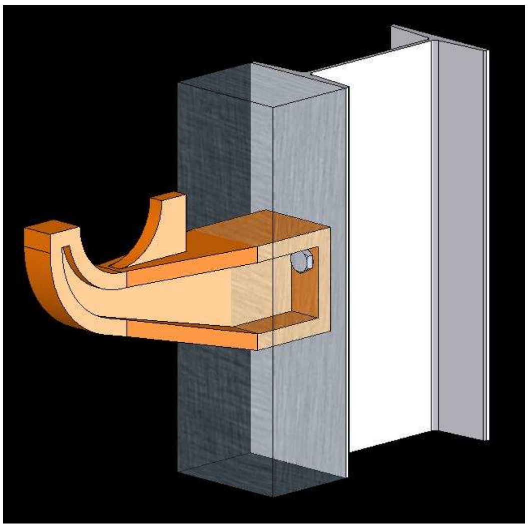

Figure 2. Heater Lateral support.

This optimization study adopts as the geometry of the lateral support the shape shown in Fig. 2. Such kind of geometry is used in most of the Petrobras refineries. The program FurnaceLSupport considers the variables necessary for the specification of a lateral support with this typical geometry. Table 1 and Fig. 3 show the variables needed for a support design using the FurnaceLSupport Program.

Table 1. Some of the design variables needed for a support.

Variable	Description
L	distance from the wall of the refractory to the centerline of the saddle
REFR	thickness of the refractory in the furnace wall
SLQ	acceptable long-term stress
SSQ	acceptable short-term stress
P	load applied on the support
SLM	maximum long-term stress
SSM	maximum short-term stress
WEIGHT	weight of the support

The variables A1, A2, B1, B2, H1, H2, T and TA represent the geometric parameters of the support. Figure 3 shows in detail the support geometry and the definition of those variables.

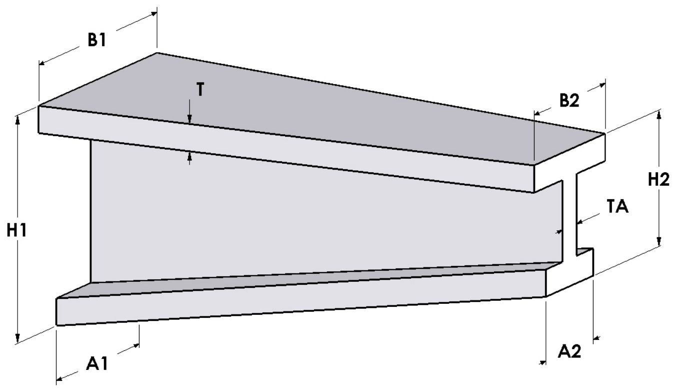

Figure 3. Geometric variables of the support.

For the geometric representation of the support, the parameter L must be defined by the designer. This is a fixed parameter which depends on the place where the tube is located inside the furnace and is independent of the mechanical design of the support. The variable REFR is defined as a function of the material used in the refractory.

Variables SSQ and SLQ are function of the material and temperature defined in the design and are obtained from API560 code (API STANDARD 560, 2001). The load applied on the support, variable P, is obtained from the support configuration inside the furnace, the material of the tube coil and the fluid inside the tube.

The last three variables, SSM, SLM and WEIGHT, are the output variables obtained from FurnaceLSupport program. The WEIGHT is obtained as a function of the geometric variables specified by the support designer. SSM and SLM are variables calculated by the program and their values are supplied to the user who must verify if those values are below the allowable values SSQ and SLQ.

The purpose of this work is the optimization of the furnace lateral support using Genetic Algorithms. The evaluation of each candidate solution is obtained by the design philosophy currently performed by the FurnaceLSupport program. This program follows design recommendations of API560 (2001). It is necessary to define the design variables used on the support optimization and which ones will be the fixed parameters with pre-defined values for REPAR refinery.

3. GENETIC ALGORITHMS

Genetic algorithms (GA) can be considered as a controlled random walk, they efficiently exploit information from previous configurations to generate new configurations with improved performances expected (Goldberg, 1989). GA are formed principally with three operators; selection, crossover and mutation. Numerous operator types are described in the literature depending on the problem to be solved and the coding used to represent the candidate solutions. Imagination is the only limit to the development of new operators. Michalewicz (1994) gives a detailed description of the different selection, crossover and mutation types.

Genetic algorithms use a population of candidate solutions (individuals) that evolve over a number of generations. Each individual is represented by its genetic material, called chromosome. For optimization purpose, the chromosome is composed by the design variables. Different kinds of coding the chromosomes are possible.

GA has three major applications, namely, intelligent search, optimization and machine learning. Currently, GA is used along with neural nets and fuzzy logic for solving more complex problems. A GA evolves through a simple cycle of stages:

(1) Creation of a population of candidate solutions,
(2) Evaluation of each solution,
(3) Selection of best solutions,
(4) Genetic manipulation to create a new population of solutions.

Each cycle in GA produces a new generation of possible solutions for a given problem. In the first phase, an initial population describing representatives of the potential solution is randomly created to initiate the search process. The performance of the individuals, called fitness, is evaluated with some functions, representing the objective and the constraints of the problem. The chromosomes are selected based on their fitness for a subsequent genetic manipulation process. It should be noted that the selection process is mainly responsible for assuring survival of the fittest individuals.

4. FURNACE SUPPORT OPTIMIZATION

4.1 Support design

The weight of the support is obtained through an approximate calculation, sub-dividing the structure into several parts and obtaining the approximate volume of the support. To obtain the weight of the component, the total volume is multiplied by the specific weight, whose value is 7.8×10^{-5} N/mm^3. Eqs.(1 to 6) following, are used to obtain, initially the volume of the support and then its weight.

$$V_1 = \left(A1 \times REFR + (A1 + A2) \times \sqrt{\left((H1 - H2)^2 + L^2\right)}/2 \right) \times T \quad (1)$$

$$V_2 = (B1 \times REFR + (B1 + B2) \times L/2) \times T \quad (2)$$

$$V_3 = ((H1 - 2\times T) \times REFR + (H1 + H2 - 4\times T) \times L/2) \times TA \quad (3)$$

$$V_4 = A1 \times H1 \times 1.5 \times TA \quad (4)$$

$$V = V_1 + V_2 + V_3 + V_4 \quad (5)$$

$$WEIGHT = V \times 7.8E^{-5} \quad (6)$$

The design of the lateral support of heaters is based on API STANDARD 560 (2001), which is specific for industrial heaters design. This code covers recommendations and procedures for the design of the support of the tubes running inside the heater, considering that the supports work under severe creep regime. The API STANDARD 560 (2001) establishes that the supports shall be designed considering two types of loads: long-term (the tube weights) and short-term (the tube weights + friction caused by the temporary expansion of the supported tubes). The code establishes the acceptable stresses for each of these loads and most of the times the short-term condition may be dimensioned. It also establishes that to calculate the stress a horizontal force of 0.3 times the vertical force should be added to the load.

Thus, stresses over the support are calculated for two different situations. For the long-term stress, where only the dead load acts, the force acting on the support is calculated considering a real furnace configuration, where the support reaction is calculated through a mathematical model. The support reaction obtained is equivalent to the load acting in a single lateral support. This model considers that the supports and the imposed loads are represented by a hyperstatic beam where the weight of the tube and the weight of the fluid running inside are taken into account.

The forces considered for each stress situation cause bending and cutting efforts, which are associated with tensile, compression and shearing stresses. These stresses are compared, through resistance criteria, with the specified acceptable stress value, after choosing the material to be used, through the API560 (2001). The cross section of the lateral support varies along it, then, the support was divided into a hundred of equal segments, and the maximum acting stresses SLM and SSM, which must be necessarily smaller than SLQ and SSQ, were obtained for each segment.

4.2 Problem definition

In order to determine a support configuration that complies with the required technical standards and design criteria, while presenting the lowest construction cost, an objective function must involve the search of the minimum support weight. The design constraints are implemented as penalty functions.

The structural constraints are related to long and short-term stresses and can be expressed as:

If (SLM > SLQ) then $\delta_1=1$ else $\delta_1=0$;
If (SSM > SSQ) then $\delta_2=1$ else $\delta_2=0$;

The fitness function is defined as:

$$F = f_{weight} + \sum_{j=1}^{2} 10.\delta_j \quad (7)$$

f_{weight} function represents the WEIGHT variable of the support (Eq. 6).

4.3 Algorithm definitions

This study applies Genetic Algorithm for the furnace support optimization. The adopted parameters of the algorithm were the ones suggested in literature for the canonical GA (Corriveau *et al.*, 2009). The initial population, set to 100 individuals, was randomly generated taking into account the limits defined for the design variables. After evaluation of each individual of the population it was performed the selection of pairs for reproduction. The most adapted individuals were probabilistic selected, which means that the best ones have more chances to reproduce. After that, it was performed crossover and mutation with a pre-defined probability, p_c and p_m , respectively. The convergence criterion adopted was the maximum number of generations, set to 100. The design variables were represented by real codification. Table 2 presents the summary of the parameters used for GA.

Table 2. Parameters of GA.

Parameter	Value
Population size	60
p_c	0.8
p_m	0.005
Tournament competitors	2

The crossover used is the arithmetic type (Michalewicz, 1994), with a rate of 0.8. Mutation is performed through the random selection of a new value for a certain design variable among the pre-established limits, defined in Tab. 3, with a 0.001 rate. After applying these operators a new generation is obtained. The best individual is obtained at the end of the evolution.

5. EXPERIMENTS

A design of a furnace previously performed for Petrobras REPAR (Paraná Refinery) refinery was chosen in this study to compare the WEIGHT of the lateral support with the result obtained through a Genetic Algorithm. In the design for REPAR the material used in the F-2102 A/B furnace was identified as: ASTM A297, HP Grade (25Cr-35Ni+Nb).

Initially, the geometric values adopted in the design of the support and their upper and lower limits were defined. Table 3 shows these parameters.

Table 3. Design variables.

Design variable	Lower bound (mm)	Upper bound (mm)
A1	60	195
A2	30	90
B1	65	195
B2	30	90
H1	70	230
H2	40	120
T	5	30
TA	5	30

In this study, the remaining variables of the support were considered constant. The following Table shows the values of those variables for the Atmospheric Distillation (U-2100) design of REPAR refinery.

Table 4. Fixed design variables.

Design variable	Value
L	255 mm
REFR	130 mm
SLQ	5.9 MPa
SSQ	11.8 MPa
P	3040 N

Several experiments were conducted, considering the parameters adopted for the Genetic Algorithm, aiming at obtaining a lateral support with minimum weight and considering the constraints imposed. Table 5 shows the variables obtained by the GA tool developed especially for this study. The last line of this table presents the WEIGHT of the support which was the result obtained for the best individual, at the end of 100 generations. The values presented under “Reference design” represent the geometric parameters for the support at the furnace of REPAR refinery.

Table 5. Results.

Design variable	Reference design	GA
A1	130 mm	83.7 mm
A2	60 mm	44.4 mm
B1	130 mm	160.8 mm
B2	60 mm	42.9 mm
H1	150 mm	93.3 mm
H2	75 mm	82.6 mm
T	20 mm	8.7 mm
TA	15 mm	5.4 mm
WEIGHT	204 N	99 N

Figure 4 shows the evolution of the process. It can be observed that the value of the fitness function of the best individual is maintained constant from the eleventh to the hundredth generation. The average fitness function value increasingly approaches the curve of the best individual fitness showing the convergence of the process. The best individual obtained throughout de process does not violate any stress constraints.

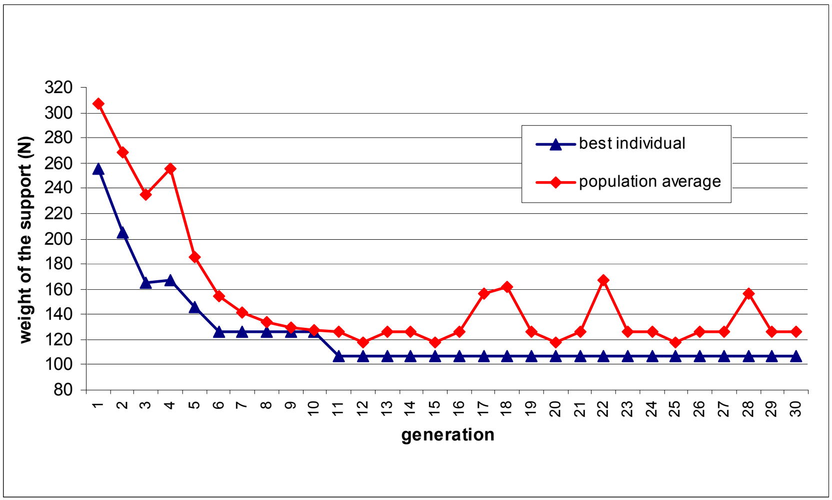

Figure 4. Evolution process.

The final value of the furnace lateral support weight obtained by GA is 99 N. The actual weight of the supports of REPAR refinery designed by the company engineer team is 204 N. The reduction of structure weight using the GA tool is 51.5% of the weight currently in use in Petrobras refinery furnaces.

6. CONCLUSIONS

This study showed that a reduction of 51.4% on the weight of the furnace lateral support can be obtained using the proposed optimization tool. This comparison was made with the weight of a real support in Petrobras REPAR refinery.

The Genetic Algorithm presented in this study was applied in an efficient manner to the lateral supports of refinery heaters, but may be applied, as well, to other components.

The algorithm presented in this paper allows obtaining a lateral support for refinery heaters with minimum weight which meets the structural restrictions presented in section 4.2 of this paper. Those constraints were considered as static penalty functions. Future studies will incorporate recent techniques of dynamic penalty to the algorithm, in particular the adaptive penalty method (APM) from Lemonge and Barbosa (2002, 2003 e 2004).

Some real data, supplied by companies that manufacture the lateral support of refinery heaters will be incorporated to the optimization algorithm in future works. The lateral supports are manufactured through a casting process and, therefore, there are some extreme values that the foundry imposes to the design variables of the component as a condition for manufacturing the support. For example, thickness over 50 mm is not used, due to the difficulty of making an X-ray of the critical parts of the component.

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