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BOILER INLET DUCT SHAPE DESIGN OPTIMIZATION FOR COMBINED CYCLE POWER PLANTS

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ABSTRACT:
A particular kind of industrial boilers, referred to as Heat Recovery Steam Generators (HRSGs), are used in combined cycle power plants to recover part of the heat of the exhaust gases of a gas turbine to generate steam and power a steam turbine. Ever since the use of HRSGs for power plants, the shape design of the inlet duct at the entrance to these units, one of their most critical components, has followed greatly unchanged design guidelines. The contribution of this paper is twofold: on the one hand, it shows that there is substantial room for improvement in the shape design of the inlet ducts of HRSGs, in terms of achieving a lower pressure drop, a higher velocity uniformity and an important cost reduction of the unit; on the other hand, it shows how the application of the Combined Hybrid Direct Search (CHDS) algorithm, applicable in many fields for aerodynamic shape optimization involving big displacements, can find these improved designs, which can be quite unconventional and non-intuitive. The CHDS algorithm combines genetic, gradient and swarm search intelligence in every iteration. The results obtained for the two HRSG families presented show that there are optimum trade-off design points with simultaneous reductions in pressure drop of up to 20-25%, in lateral surface of up to 38% and in length of up 16%, while having comparable velocity uniformities to the existing designs.

Keywords: aerodynamic optimization, optimization methodology, multi-attribute, hybrid direct search, geometry parameterization, computational fluid dynamics, heat recovery steam generators.

RESUMEN:
Un tipo particular de calderas industriales, denominado calderas generadoras de vapor por recuperación de calor (HRSGs, en sus siglas en inglés), se utiliza en centrales de ciclo combinado para recuperar parte del calor de los gases de escape de una turbina de gas, generar vapor y alimentar una turbina de vapor. Desde el comienzo del empleo de los HRSG para centrales eléctricas, el diseño de la geometría del conducto de entrada a estas unidades, uno de sus componentes más críticos, ha seguido pautas que han evolucionado muy poco. La contribución de este trabajo es doble: por un lado, muestra que existe un potencial sustancial para mejorar el diseño de la forma de los conductos de entrada de los HRSG, en términos de lograr una menor caída de presión, una mayor uniformidad de velocidad y una reducción importante del coste global de la caldera; por otro lado, muestra cómo la aplicación del algoritmo combinado de búsqueda directa híbrida (CHDS, en sus siglas en inglés), aplicable en muchos campos para optimización aerodinámica de geometrías, permitiendo grandes desplazamientos, puede encontrar estos diseños mejorados, que pueden ser bastante poco convencionales y no intuitivos. El algoritmo CHDS combina inteligencia genética, de búsqueda de gradiente y de búsqueda de enjambre en cada iteración. Los resultados obtenidos para las dos familias de HRSG presentadas muestran que hay puntos óptimos de diseño con reducciones simultáneas en la caída de presión de hasta el 20-25%, en superficie lateral de hasta el 38% y en longitud de hasta el 16%, manteniendo niveles de uniformidad de velocidad comparables a diseños existentes.

Palabras clave: optimización aerodinámica, metodología de optimización, multi-atributo, búsqueda directa híbrida, parametrización geométrica, dinámica de fluidos computacional, calderas generadoras de vapor por recuperación de calor.

1.- INTRODUCTION

Heat Recovery Steam Generators (HRSGs) for combined cycle power plants are a key industrial equipment in the power generation sector. They are designed and manufactured by big engineering companies and they are both expensive, large in size, and crucial to the performance of the power plant. However, the design of certain critical components, such as the inlet duct, has remained largely unchanged for many decades. Their performance is mainly measured in terms of pressure drop throughout the unit, gas flow velocity uniformity and heat transfer capacity.

In an HRSG, the hot exhaust gases of a gas turbine flow through a set of tubes (normally finned tubes) through which water is pumped. The heat of the gas flow is transferred to the water flow, which is transformed into steam. This steam can be used directly for industrial applications, or for electricity generation in a steam turbine, or for both (in the so-called co-generation plants).

Figure 1 shows an example layout of a combined cycle power plant, an example of a real HRSG and several inlet duct design types, along with an example velocity flow distribution inside an HRSG.

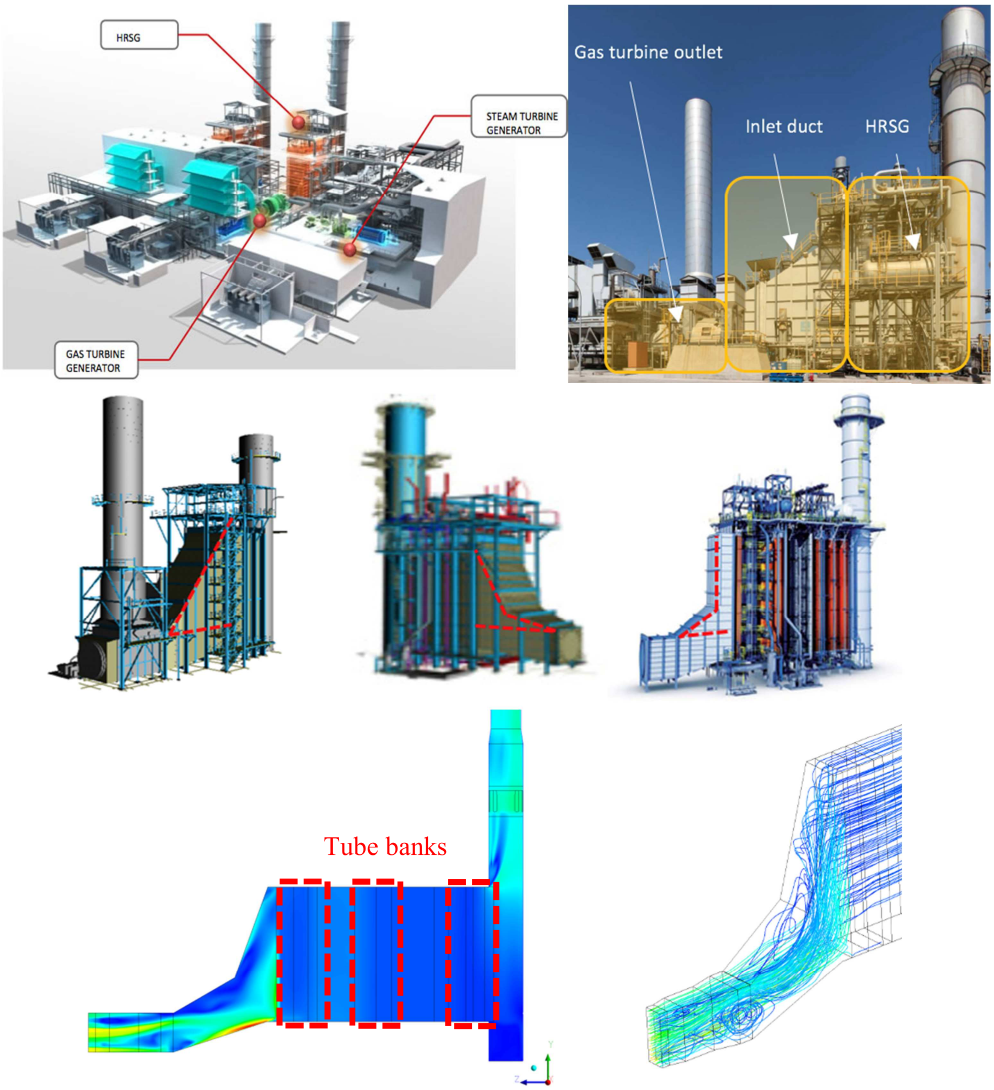

Fig. 1. Examples of a combined cycle power plant layout and real HRSG (top). Below, HRSG inlet duct design types most widely used in industry (from left to right): single angle inlet duct, double angle inlet duct and alternative design type that some manufacturers are starting to use. At the bottom, side view of velocity contours in the mid-plane of a typical HRSG (left), illustrating the position of the different tube banks; detailed isometric view of velocity magnitude streamlines in the inlet transition duct (right). Velocity values range from 0 (blue) to 100 m/s (red) – detailed scale cannot be included for confidentiality reasons.

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The main challenge in this application is that the exhaust gas flow exiting the gas turbine has to flow into the HRSG, which has a much bigger cross-sectional area, through a critical section, the so-called inlet duct. This introduces flow detachment and hence turbulence and velocity non-uniformity, which can be observed in Figure 1 (the velocity profile exiting the gas turbine greatly influences flow performance depending on its velocity uniformity, swirl and other characteristics). Despite this, all manufacturers try to make this inlet duct as short as possible, to make their whole units shorter and more compact, while gas pressure drop and gas velocity profile are maintained within certain limits, which facilitates their integration into the power plant layout. Furthermore, reducing the size of the inlet duct can reduce manufacturing costs considerably, since this section is built of very costly stainless steel (currently, the average manufacturing cost of an HRSG inlet duct is around 450 $/m2).

Over the decades, HRSG inlet ducts have been designed following largely the same design trend-lines. This paper focuses on the shape design optimization of the inlet duct of different HRSG families, thanks to the application of the CHDS algorithm presented in 1.

Broadly speaking, the design of an HRSG inlet duct has up to date always been of one of the two types shown in Figure 1 (middle let and middle center).

However, certain manufacturers have started using alternative inlet duct designs, as can be seen in Figure 1 (middle right), but extensive design analyses have not been performed, as far as it is known, to compare the different inlet duct designs alternatives thoroughly.

There are a number of works in the area of Computer Fluid Dynamics (CFD) modelling of an HRSG's inlet duct, but to the authors' best knowledge, a complete shape optimization analysis of this critical element has never been addressed. The aim of these works is to analyze the flow distribution of a particular design, or the effects of elements introduced in the inlet duct to improve the flow distribution, such as 2 and 3. More general works in the field of CFD analyses of complete HRSGs can be found in 4-10.

The aim of applying the CHDS algorithm to the design of HRSGs is to yield optimized geometries for the inlet ducts of a wide range of HRSG families, which can improve the current design trend lines and offer better performance levels, with shorter and more compact units, while having a good velocity uniformity at the HRSG inlet. This is the main contribution of this paper.

The paper is organized as follows: Section 1 describes the shape design optimization problem of a generic HRSG parameterized inlet duct; Section 2 describes the main results obtained for two HRSG families with the CHDS optimization algorithm and offers an in-depth analysis of the results; and, finally, Section 3 summarizes the main conclusions drawn from this work and presents the future work to be carried out in this area.

2.- SHAPE DESIGN OPTIMIZATION PROBLEM DESCRIPTION

The objective of this paper is to obtain optimum designs for the inlet duct of a set of HRSG families. The optimization problem is multi-attribute or multi-objective, since the final goal is to obtain the inlet duct designs which minimize two attributes: total pressure drop across the inlet duct and velocity non-uniformity in the outlet plane of the inlet duct.

The pressure drop is measured as the difference in mass weighted average of the total pressure between the inlet and the outlet of the inlet duct.

The velocity non-uniformity is defined as the difference between the velocity area-weighted average and the mass-flow-weighted average. This definition is simply one of the possible ways of measuring velocity non-uniformity. Other alternative definitions would be, for example, checking the difference between the maximum velocity, the minimum velocity and the average velocity (as is done for velocity indexes, for instance); or comparing the maximum and minimum velocities, etc. However, these alternative definitions, involving the maximum and minimum velocity values, can be misleading, since minor mesh irregularities, inevitable in most CFD simulations, can yield false values of maximum or minimum velocities. These values are acceptable numerical errors and can be easily discarded by the engineer when evaluating the results one by one and manually, but cannot be detected by the CFD code when launching an automatic optimization. Therefore, the indicated definition of velocity non-uniformity is used. It must be noted that, strictly speaking, by velocity non-uniformity we are not only referring to the fact that velocity values are uniform in the outlet plane of the inlet duct, but to the fact that the mass flow must also be distributed as evenly as possible and the "combination" of velocity and mass flow uniformity is given by the difference between the velocity area-weighted average and the mass-flow-weighted average.

Both attributes are handled in per unit magnitude, so that the fact that the absolute magnitude values of each attribute have a different range does not distort the optimization process or the final results. The optimum designs are those which minimize both attributes.

The inlet duct geometry is parameterized, as shown in Figure 2. The variables used are: two angles for the top wall, two angles for the lateral wall (identical on both lateral walls), two more for the bottom wall and the total length of the inlet duct. These variables take into consideration the design modifications which are feasible in terms of manufacturing and assembly in real power plants. For example, curved walls or more intermediate angles are not considered of interest and they are consequently not included in this analysis.

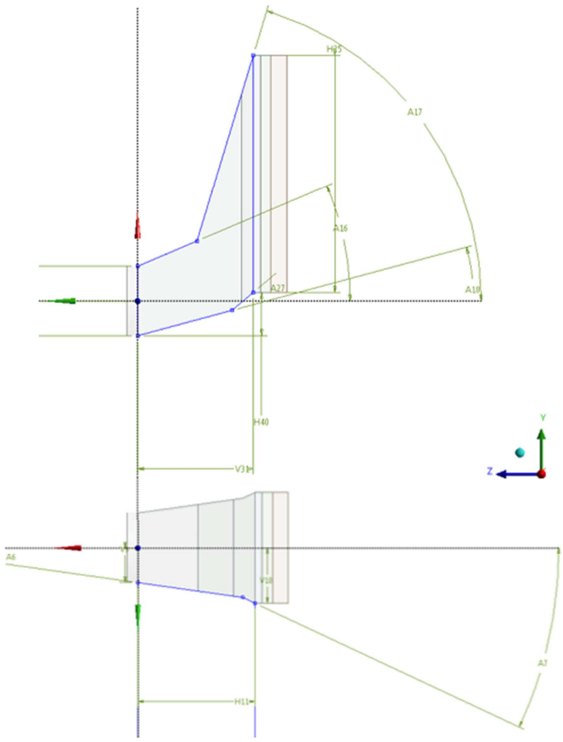

Fig. 2. Variables used to parameterize a general inlet duct for different HRSG families (side and top views).

3.- MAIN RESULTS OBTAINED WITH THE CHDS OPTIMIZATION ALGORITHM

This section presents the applicability of the CHDS algorithm (as described in detail in [1]) to other fields in which shape optimization can be used successfully, namely to the design optimization of HRSG inlet ducts for combined cycle power plants.

Although CHDS is explained in depth in [1], a brief summary is included here for the reader's comfort. Figure 4 (top) illustrates the main steps followed by a general CHDS optimization procedure:

1. Phase 0 is the design exploration phase, in which a number of design points are generated and computed to have an initial representation of the space of attributes (i.e. the performance space). These points can be generated by means of any Design of Experiments (DoE) technique, or other methods.
2. A first Pareto front can be computed, to group the optimum designs for phase 0. The Pareto front is a very useful tool for true multi-attribute optimization problems, as commented below.
3. A tolerance threshold is automatically generated, based on the expert's settings, to group the candidate points that will be selected for the next phase. Clustering can be applied to select representative points among a group of very similar design points (both in the space of variables and in the space of attributes).
4. A crossover is performed between each selected design point and its closest point(s) on the Pareto front. The crossover is controlled by the so-called increment factors, which are automatically tuned to improve the optimization speed and final result.
5. A new set of design points is hence generated. These points constitute phase I.
6. A new Pareto front is computed. The optimization has proved successful if the new Pareto front improves the Pareto front of phase 0.
7. This procedure can be repeated as many times (i.e. phases) as set by the expert.

CHDS exploits the concepts of variable hierarchy (also allowing for continuous and non-continuous variables) and optimization phases and it combines gradient, genetic and swarm search intelligence for a true multi-attribute, structured, hybrid direct search optimization.

The novelty of the proposed CHDS approach stems from the fact that, as opposed to most other authors who have combined gradient-based and non-gradient-based algorithms (relevant examples are [11-13]), CHDS does not switch from one type of algorithm to the other depending on how the optimization is advancing, but it combines elements of both types of algorithms in every phase.

The aim of this section is to show that the CHDS algorithm can be applied successfully to the shape optimization of HRSG units, yielding improved performance, cost competitiveness and, in some cases, quite unconventional designs with proved enhancements over current HRSGs.

This work has been carried out for various HRSGs families of a particular manufacturer and therefore some of the results cannot be shown fully for confidentiality reasons.

The main concern of most HRSG manufacturers nowadays is to meet the requirements of the final client, and even improve them to be better than their competitors, while reducing the overall cost of the unit. The main requirement for a modern HRSG is keeping the pressure drop across the whole unit below a maximum allowed threshold, while recovering the maximum heat available from the gas stream. An additional and very important competitive advantage, as has been mentioned above, is being able to meet the performance requirements with smaller units (mainly reducing the total length).

The application of the CHDS algorithm to this particular case of shape design optimization has produced very interesting results. In the first place, to show the performance difference of various HRSG design alternatives, so that it is clear that it is worth applying an optimization scheme in the first place, two different designs and their performance results are depicted in Figure 3.

The first design alternative is the design which was used for the real power plant, in the particular case of one of the studied HRSG families, and which is currently in operation (single angle top plane for the inlet duct). This is a more traditional design. On the other hand, the second design alternative has a double angle top plane for the inlet duct, which is a design feature that many manufacturers introduced already years ago, because it supposedly had an improved performance over the single angle design (it is also shown in this paper that the double angle design is not always better than the single angle design).

The performance results for both design alternatives, in terms of pressure drop and velocity uniformity, are shown in Figure 4. There is a considerable improvement in terms of pressure drop with the alternative design, so it is worth

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exploring more design points to have a better view of where the optimum designs may be and if other more unconventional designs yield improvements in performance.

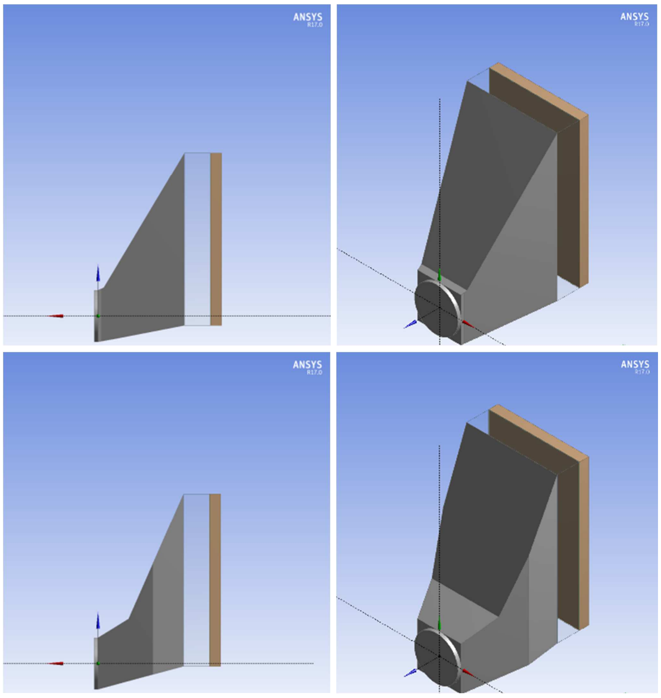

Fig. 3. Side and isometric views of two example design alternatives for the inlet duct of an HRSG (single angle top plane and double angle top plane for the inlet duct). These are the real current design (top) and an alternative design (bottom) for the first HRSG family presented in this paper.

The application of CHDS has a phase 0 or design exploration phase which, in this case, has 120 design points. These points can be obtained by DoE techniques, such as Latin Hypercube, or other methods especially recommended, for instance in [14], for problems similar to this one. In the case of this paper, a custom DoE scheme was used, based on the authors' experience, but Latin Hypercube and other methods will also be tested in future work.

Once the exploration phase has been completed, CHDS carries out the optimization itself. The results of a one phase optimization for two HRSG families are depicted in Figure 4.

One of the most powerful representations to understand the simulation results of a multi-attribute optimization problem has been used in Figure 4. It is called the Pareto front. The Pareto front shows the family of optimum solutions, taking into account all the attributes or objectives considered (in this case, total pressure drop across the inlet duct and velocity non-uniformity at the outlet plane of the inlet duct). All the solutions on the Pareto front are equally optimum, since the absolute optimum would be to have pressure drops and velocity non-uniformities as close to zero as possible, and therefore each of the solutions on the Pareto front are a potential optimum combination of pressure drop and velocity non-uniformity.

In general terms, designs with a low first angle of the top wall and high second angle yield reduced pressure drops, because the flow is more constrained and cannot detach as easily. However, the velocity uniformity is worse because of the abrupt second angle of the top wall. Conversely, if the first angle is increased and the second angle reduced, flow separation will occur at some point and hence pressure drop will increase, but velocity uniformity is improved. Similar analyses can be carried out with the rest of the design variables.

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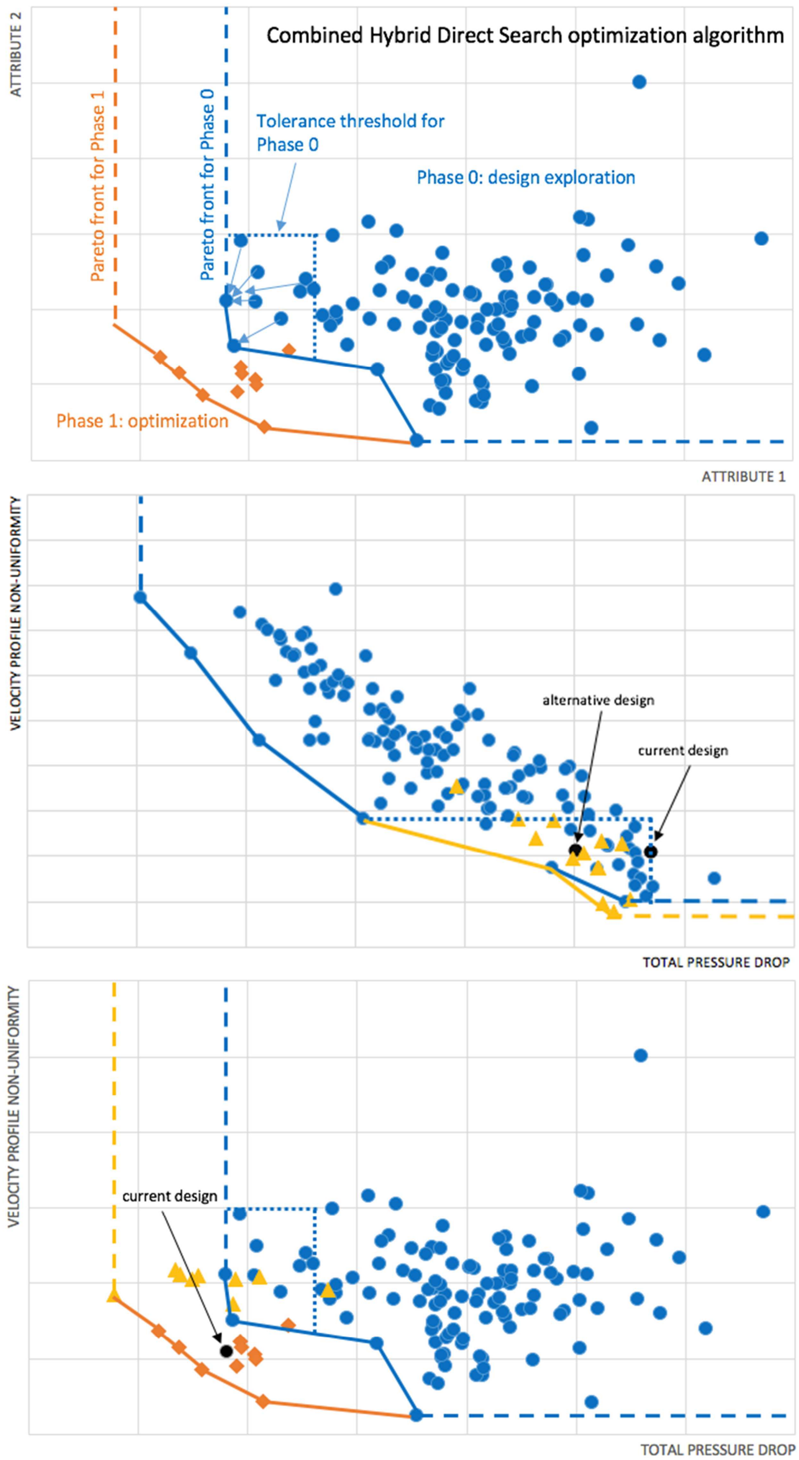

Fig. 4. Illustration of the procedure followed by the CHDS optimization algorithm for a one-phase optimization (top); application of the CHDS algorithm to the shape optimization of the inlet duct of two HRSG families for combined cycle power plants (middle and bottom). Two value sets are used for the variable increment factors (as explained in [1]) for the crossover process: below unity (candidate points marked with triangles) and above unity (candidate points marked with diamonds).

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Before the results of Figure 4 are analyzed, a brief section is presented on the validation of the results of the CFD solver used (ANSYS v17.0) for the evaluation of HRSGs. The following table presents the comparison of the pressure losses provided by the manufacturer and the pressure losses obtained from the CFD simulation for each one of the tube banks which are located throughout an HRSG and through which water is pumped to generate steam. This is a typical comparison to validate any CFD simulation applied to HRSGs. For clarity, the tube banks were shown for an example simulation in Figure 1.

Tube bank	Error [%]
#1	9
#2	9
#3	7
#4	3
#5	5
#6	1
#7	2
#8	4
#9	5
#10	5
#11	4
#12	4
#13	4
#14	4
#15	5
#16	5
#17	5
#18	5
#19	6
#20	8

Table I . Relative error between the pressure losses as provided by the manufacturer and as obtained from the CFD analysis for the tube banks of an example HRSG.

There are certain errors between the values provided by the manufacturer for the pressure losses and the values obtained from the CFD simulation. These differences are mostly due to the non-uniformity of the velocity distribution at the entrance of each one of the tube banks (simulated as porous media), whilst the porous media equations assume a homogeneous velocity profile. Besides, the pressure losses provided are point measurements and their values are affected by the exact position of the reading within each tube bank's inlet/outlet plane. In any case, the errors are very acceptable, given the application and the absolute pressure values, which mean that the absolute errors are of very few Pascals.

Focusing now on the results of Figure 4, it can be observed how the application of the CHDS algorithm has produced an improvement of the performance result of an HRSG.

Although phase 0 selects the design points following a procedure which covers the area of the search region the designer is most interested in, this phase in itself is a mere design exploration and not an optimization as such. Phase I is the first true optimization phase of the CHDS algorithm.

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It must be noted, in any case, that the design exploration procedure built into CHDS to carry out the analyses for phase 0 is already quite good in many cases, since the design points calculated yield good performance results and cover a broad area of the space of attributes (or objectives). Hence phase 0 is in itself valuable in the sense that manufacturers have not performed such an extensive exploration of different design points, in most cases. It can be seen that the current design trend-lines (i.e. using a single angle design or, alternatively, believing a double angle design is always better) can be misleading or, at least, not optimum. Moreover, unconventional and non-intuitive designs can prove to outperform traditional designs.

As an example of this, Figure 5 and Table 2 include the comparison between several representative design points, among all those simulated in Figure 4.

In this figure and table, it can be observed that designs which are very similar (i.e. close in the space of variables) and which would intuitively be very close also in the space of attributes (i.e. have a very similar performance), may really be far apart in their results, whereas quite different designs may perform very similarly. It is worth highlighting, in particular, that double angle designs are not necessarily better than single angle designs (for instance, design points d and g are very close in performance). This means a thorough analysis is required in each case, because traditional design trend-lines may not always be the best option. Furthermore, both phase 0, as an exploration phase, and, most importantly, phase I, may yield unconventional designs or designs with a non-intuitive performance (design point i and, especially, j).

All the results of Figure 5 support the importance of applying and optimization methodology, be it CHDS or others, to the problem of inlet duct design in HRSGs for combined cycle plants.

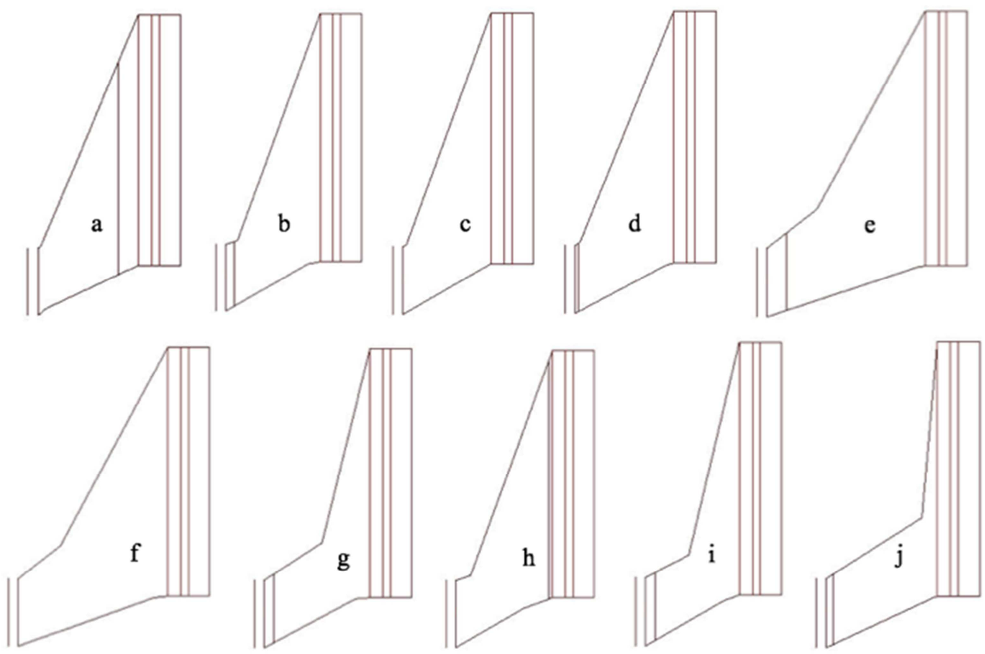

Fig. 4. Side view of example design points which are very close in the space of variables and also very close in the space of attributes (a to d); very close in the space of variables and quite apart in the space of attributes (e and f); quite apart in the space of variables and very close in the space of attributes (g and h); and design points which are quite unconventional (because they are quite radical designs) and somewhat non-intuitive in their performance (i and especially j).

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Design point	Total pressure drop	Velocity non-uniformity
a	72%	146%
b	72%	145%
c	72%	145%
d	75%	139%
e	98%	89%
f	96%	102%
g	71%	139%
h	73%	141%
i	64%	146%
j	60%	159%

Table II . Comparison between different design points, to show that points which are very close in the space of variables can also be very close in the space of attributes (a to d); points which are very close in the space of variables can also be quite apart in the space of attributes (e and f); points which are quite apart in the space of variables can also be very close in the space of attributes (g and h); and example design points, which are quite unconventional and somewhat non-intuitive in their performance (i and especially j). All results are with respect to the attribute values of the current HRSG design of Figure 4 (middle).

In phase I, as a whole, the design points improve the performance results of the design points studied in phase 0. Additionally, it can be observed how the application of CHDS improves the Pareto front obtained in phase 0 and hence the performance results of the optimum design points. The geometries of the optimum designs obtained are, in some cases, quite unconventional and non-intuitive, as seen in Figure 5. All this has allowed the manufacturer to have a new set of design guidelines for its different HRSG families for the coming years.

Besides, the manufacturer has received Pareto fronts, similar to those shown in Figure 4, for each of its main HRSG families. This allows for a well-based trade-off between total pressure and velocity non-uniformity, because, for a particular type of HRSG, design points with lower total pressure drops may be preferred, even at the expense of higher non-uniformities, or vice versa. The exact geometries obtained for the optimum design points cannot be included in this document for confidentiality reasons.

To have a better insight into the true potential of CHDS for shape design optimization involving big displacements, the algorithm is applied to a second HRSG family, and very interesting results can be observed in Figure 4 (bottom).

In particular, for this case, the design exploration carried out in phase 0 (candidate points marked with circles) covers a broad area of the search region, but yet the real existing design, already built and in operation for this particular HRSG family, dominates all the other candidates, i.e. it has better values for both attributes. This means that a mere design exploration can be inadequate or not good enough in some cases. Once CHDS computes the points for phase I, the simulations show that phase I candidate points improve considerably, not only points in phase 0, but, most importantly, the real current design of this HRSG.

For this second example HRSG, an additional test has been performed. The variable increment factors used to obtain new candidate design points for phase I from the crossover of their parents of phase 0 are changed (the variable increment factors are explained in detail in 1). In particular, two sets of values are used. The first set (candidate points marked with triangles) has variable increment values below unity, which means that the crossover of the parent solutions lies between both parents (in the space of variables). The second set (candidate points marked with diamonds)

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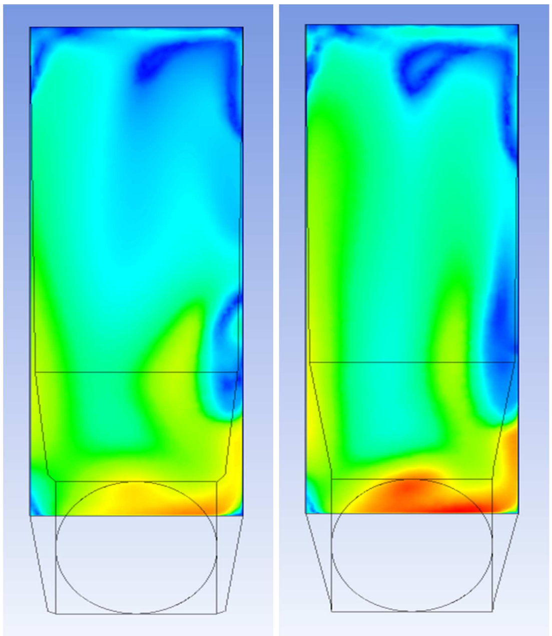
has variable increment values above unity, which means that the crossover of the parent solutions lies beyond the parent point belonging to the Pareto front (it is always checked that the new variable values lie within that variable's value range, as defined by the designer).

For this case, the use of increment factors above unity yields better results, in general. However, the best candidate point in terms of total pressure drop is obtained with an increment factor below unity. Hence the bottom line is that both sets of values should be exploited by CHDS to have a higher probability of reaching optimum designs.

Finally, to further illustrate the performance of the optimum designs, two of the design points on the Pareto front for each HRSG family are presented in Figure 6. It shows the velocity profiles at the outlet of the inlet duct, to depict the level of uniformity achieved after the optimization. It must be noted that, due to manufacturing, cost and plant-layout constraints common to current HRSGs, the designs still have a level of flow detachment and non-uniformity. Uniformity is thereafter highly improved as the gases flow through the tube bundles.



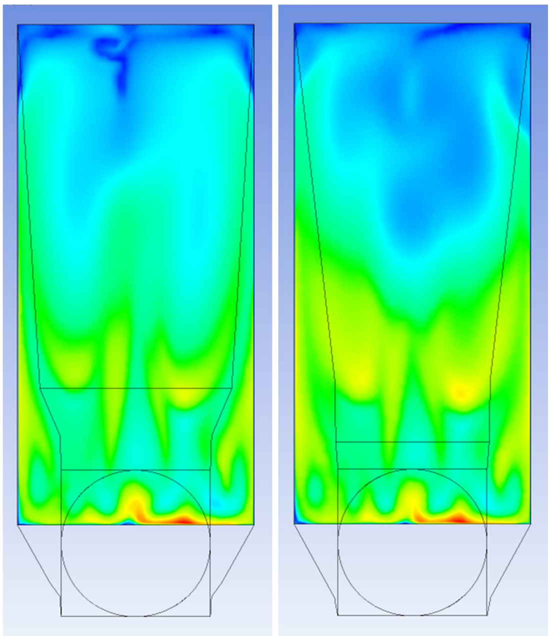


Fig. 6. Velocity contour plots for the outlet plane of the inlet duct: contour plots for recommended designs, with improved uniformity with respect to current designs (left); and for designs with worst uniformity, but within the Pareto front (right), for first HRSG family (top) and for second family (bottom). Velocity values range from 0 (blue) to 100 m/s (red) – detailed scale cannot be included for confidentiality reasons.

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