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Building Operations Maps: An Effective Tool for Improving Gasifier Operations in IGCC Power Plants

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Abstract

IGCC technology has demonstrated its feasibility, but efficiency and reliability can still be improved. Therefore, an operations map is presented as a tool for optimising gasifier operation. To demonstrate this, two models of entrained flow gasifiers (one simple and the other more complex) are validated with a large set of actual plant periods of operation. The two models are used to build operations maps, which are graphs where the main gasification parameters are related to the degrees of freedom that the operator has. A comparison of the two maps allows one to see the limitations of the simple model and to understand the gasifier's operation. To construct the maps, a general method for building experimental operations maps from only plant data is required and, thus, needed to be developed. When the method is applied to the gasifier, the tendencies of the maps are the same as those of the model-made maps. Operations maps are, therefore, practical tools that help to operate and diagnose a system (e.g., a gasifier). They allow one to understand how it works, how to optimize its operation, and how to avoid faulty operation which may cause the plant to shut down.

Keywords: Gasification, IGCC, operation, optimisation.

1. Introduction

Coal gasification is an efficient and environmentally friendly way to use coal, not only to generate electricity in Integrated Gasification Combined Cycle (IGCC) power plants but also to produce hydrogen and syngas for the chemical industry (Pisa, 1996; Stiegel and Maxwell, 2001; European Commission (a), (b); Hoffman 1981). However, the correct operation of a gasifier is very complex for two reasons. First, actual operating conditions usually differ from design conditions because experience in the gasifier's operation is very small compared to expertise with conventional equipment such as boilers. Also, the design fuel might be modified by adding coke, biomass, etc. Consequently, gasifier operation should be revised through experience.

Second, proper gasifier operation is more critical than boiler operation because it does not consist of simply maximising efficiency but also of other issues that in turn require keeping several output variables (gas composition and gasification temperature) in correct ranges and maximising fuel/gas conversion by adjusting two input variables (the oxygen and steam that are introduced in the gasifier). The gasification temperature is a variable that cannot be measured but has to be kept in the correct range because it determines not only the efficiency but also safe operation. In oxygen-blown slagging gasifiers, an error in oxygen measurement could cause either very high temperatures that can damage the equipment or temperatures under the slagging point that can stop slag flow and produce blocking. Furthermore, although output variables could be considered separately, a modification in an input variable implies changes in all output variables so that all dependencies should be understood and integrated. Thus, to operate the gasifier it is necessary to use criteria corresponding to the gasifier operating not only in terms of tendencies but also in terms of absolute values.

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The aim of this work is to transform a hard subject that comprises several related variables into something that can be used and applied by operators and that could be implemented in the plant control system. Operators need a practical tool which helps them to adjust gasifier operations in a few minutes (perhaps seconds), taking into account several variables at the same time. Therefore, a graphic tool is proposed.

The concept of the operations map is applied to a two-dimensional graph whose axes correspond to the input variables (oxygen/fuel ratio in *x* and steam/fuel ratio in *y*) where the main output variables' (temperature, efficiency, and the concentrations of the main components of the gas) evolution is plotted by using constant value lines. Each 2D map refers to a fixed gasifier.

Maximum and minimum values of the output variables determine the region or the window where the gasifier should be operated. Since there are two degrees of freedom, there are several ways to modify the value of an output variable, and the choice of the best one depends of the other output variables so that a graph that shows all important variables is very useful for operating the gasifier safely and efficiently.

In this paper, two models are validated with a large set of plant data and used to build operations maps. These maps can be very useful for exploring new operating zones. However, to analyse and improve actual operation it is better to take advantage of expertise by building operations maps from plant data without a model and to use model-built maps as a reference to provide theoretical support. Since, unfortunately, there were no methodologies to build operations maps from plant data, a new general method was developed and applied to the case of study: the Elcogas IGCC Power Plant in Puertollano, Spain.

As a result, maps built by using a large amount of plant data and supported by theoretical models were obtained. These maps can be very useful not only to improve future operation but also to analyse past operation. This is also a type of diagnosis because it allows a comparison of differences in gas composition and gasification temperature and the efficiency of several operating strategies. Results show that, depending on the operational mode, gasifier efficiency may vary 3 percent, which means about 5 MWe.

The Elcogas IGCC Power Plant is a demonstration project in which several European companies have worked together. CIRCE has collaborated with Elcogas for several years in plant operation optimisation and diagnosis. The main achievement of the CIRCE work is the development of the TDG system (García-Peña et al., 2000, 2001). TDG is an acronym for Thermoeconomic Diagnosis, which consists of comparing two stable real plant operating periods, determining the causes for why efficiency varies and quantifying the influence of each cause in an efficiency deviation. This information allows one to optimise the plant by comparing the influence of malfunctions in plant efficiency to the cost of solving these malfunctions.

TDG takes into account interactions between the gasifier and other devices. However, the relationship between gasifier operation and the gasifier operating properly should be rigorously investigated. In this way, the operations maps proposed here can complement the TDG system.

2. Choice of the Supporting Gasifier Model

The PRENFLO (PRessurized ENtrained FLOw) gasifier is fed with fuel (a mixture of coal and petroleum coke), oxygen, steam and nitrogen, which react at a high temperature, becoming a combustible gas (synthesis gas). This kind of gasifier achieves very high carbon conversion in a short reaction time (*Figure 1*). When the gas leaves the reaction chamber, it is quickly cooled by a flow of cold gas in order to lock the gas phase equilibrium and solidify the ash carried by the gas (most of the ash leaves the gasifier as slag that flows to the bottom). The gas is then further cooled to get the right temperature to be cleaned. The sensible heat of the gas is used to generate steam, which is then exported to the steam cycle.

Since the amount of fuel is determined by the gas demand of the turbine and nitrogen is mainly used to carry the fuel, the only degrees of freedom that the operator has to control gasification reactions are the amounts of oxygen and steam. These flows are controlled by the oxygen/fuel and steam/fuel ratios.

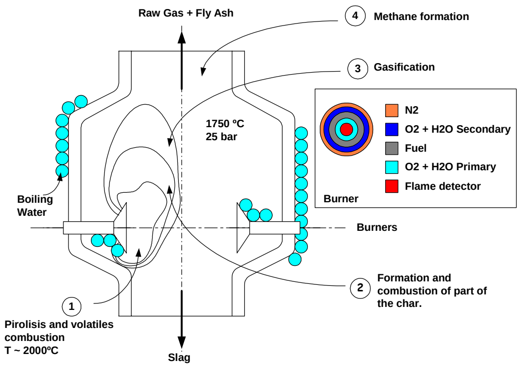


Figure 1. Reaction chamber schematic. Source: Elcogas.

Two models of the reaction chamber were available. The first one (constant fuel conversion) was proposed by Van der Burgt (Van der Burgt, 1998; Ayerbe, 2002) and was used for the fine-tuning of the control system during commissioning. This model considers a constant fuel conversion ratio, avoids the gasification process simulation, and only takes into account mass and energy balances and gas phase equilibrium.

The second model (variable fuel conversion) was proposed by Martínez (Usón et al., 2003) to be used as the off-design simulator of the gasifier in the TDG system. It divides the gasification process into several stages, studies gas-particle interaction, and simulates gas phase equilibrium. Consequently, this complex model takes into account fuel conversion variation due to gasification condition modifications.

To adjust the two models, information provided by the TDG System is used (García-Peña et al., 2000, 2001). This system connects to the plant information system and identifies stable operating periods. For each period, TDG stores and validates information and, by using data reconciliation and closing energy and mass balances, determines the thermodynamic state of the plant.

The information from 2,874 real operating periods (which means 4,812 hours) filtered and processed by this system is used to tune the models: in the model proposed by Van der Burgt, the fuel conversion ratio is adjusted; and in the Martínez model, the values of this ratio are used to adjust the particle residence time. To validate the models, the relative average experimental discrepancy (taking into account this historical data) is calculated for gasification temperatures, main gas composition, and CGE (Cold Gas Efficiency or the ratio between the chemical energy of the gas and the chemical energy of the fuel). Results are shown in TABLE I.

TABLE I. RELATIVE AVERAGE ERRORS OF THE TWO MODELS

	Constant fuel conversion	Variable fuel conversion
Temperature	2.10%	2.40%
CGE	0.26%	0.80%
CO	0.20%	0.56%
H_2	0.62%	0.43%
CO_2	1.60%	4.90%
H_2O	1.90%	5.30%
H_2S	7.70%	7.90%
COS	8.25%	8.50%

As can be seen, errors in the CGE and the most abundant species (CO, H_2) are very small. However, relative errors increase for the less concentrated species. One remarkable result is that errors of the constant conversion ratio model in CGE, CO_2 and H_2O are lower than errors of the variable conversion ratio model. This is due to the limitations of operating with actual plant data. These difficulties increase when a more complex model is used. However, errors of both models are low, and differences will be seen in the next section by comparing simulations in a zone wider than the usual operating region.

3. Model-Built Operations Maps

Once the models have been presented and validated, they are used to build reference operations maps. In *Figure 2*, an operations map built from the constant conversion model is shown. This map has been plotted by using information from a real operating period and by modifying oxygen and steam ratios. As can be seen, when oxygen or steam increases, CO_2 increases and CO decreases. When oxygen rises or steam decreases, the temperature increases and H_2 decreases. Finally, the CGE decreases when the oxygen increases and decreases slightly if the steam increases.

In *Figure 3*, an equivalent operations map using the variable conversion model is shown. In this model, when the temperature decreases, fuel conversion decreases. As a result, the CGE reaches a maximum; and, as long as oxygen decreases, fuel conversion decreases and CO and CO_2 variations are lower. As can be seen, when the oxygen ratio is high and conversion increases to 100 percent (right side of the map), the constant conversion map becomes similar to the variable conversion map; but the values are displaced. This displacement is due to the fact that fuel conversion in the constant conversion model has been adjusted to 98.5 percent. This value might seem low, but it is due to the high ash content of the fuel.

Maps built by using two models can help in comparing the models. Although both can fit plant data quite accurately, when the operating zone is expanded, they show differences. Besides, they are an example of how operations maps can be very useful to plot information in order to understand gasifier operation and to optimise it.

The constant conversion model was very useful for tuning the control system in a small operating zone, but it does not provide good results when this zone is expanded. To do so, a variable conversion model should be used. However, it might be difficult to tune this complex model with plant data corresponding to a reduced operating zone, as could be seen when both models were validated. In summary, it is better to build plant operations maps directly from plant data and to use the models to give theoretical support to the plant results. Therefore, a methodology to build operations maps from plant data will be presented and applied next.

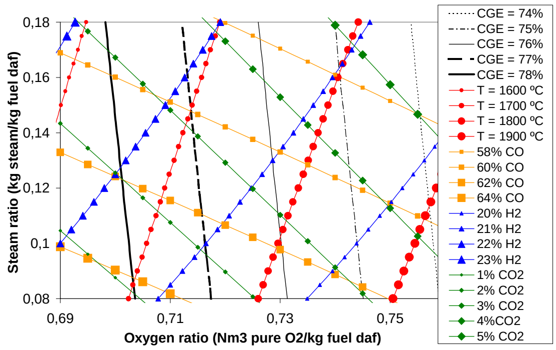
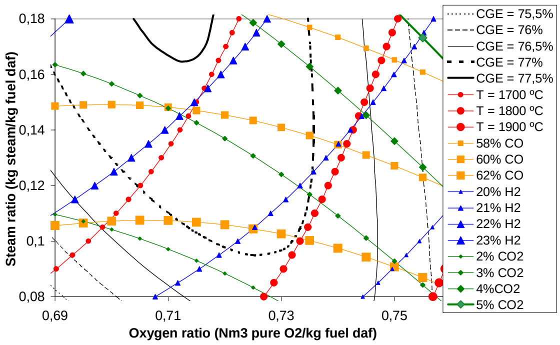


Figure 2. Constant conversion operations.



map.

Figure 3. Variable conversion operations map.

4. Methodology for Building Operations Maps from Plant Data

A method to get a family of points that corresponds to an iso-line (line of constant value of a dependent variable) on a map (constant value of a parameter) is explained. This process can be repeated for the other iso-lines, for the other values of the parameter, and for the other dependent variables until all the maps are built.

A dependent variable *z* that depends on two independent variables (*x* and *y*) and a parameter (*p*) is considered:

$$z = z(x, y, p) \qquad (1)$$

In the example of the gasifier, *x* is the oxygen ratio, *y* the steam ratio, and *p* the load. The dependent variable *z* can be temperature, CGE, or a single concentration. Graphically, the iso-line is the intersection of the surface $p = p_0$ and the plane $z = z_0$ (*Figure 4*).

A group A of operating points characterised by the values of the four variables ($A = \{(x, y, p, z)_i,\ i=1..n_A\}$ is available (the 2,874 actual operating points used to tune the models), and we want to transform it into another group of points $B = \{(x_0, y_0, p_0, z_0)_j,\ j=1..n_B\}$. The values of p_0 and z_0 are known because they are given by the map and the iso-line, respectively (e.g., 90% load and 60% CO) and are the same for all the points in B. On the other hand, x_0 and y_0 are the unknown quantities, which are different for each point in B. When the n_B pairs (x_0, y_0) are plotted, the iso-line is formed. The procedure for doing this transformation consists of building groups of four points from A and by considering that the z function is linear in small zones, obtaining one new point for B from each four-point group.

So, the first step is to make four-point groups. To select them, the following conditions are imposed:

i) Their p and z values should be near to p_0 and z_0:

$$p_0 - \delta_p \le p_k \le p_0 + \delta_p \qquad k = 1,\ldots,4 \qquad (2)$$

$$z_0 - \delta_z \le z_k \le z_0 + \delta_z \qquad k = 1,\ldots,4 \qquad (3)$$

ii) Once a point 1 that accomplishes the previous conditions has been selected, the other three points are chosen according to the following criteria:

$$(p_1 - p_0)\cdot(p_2 - p_0) > 0 \qquad (4)$$

$$(z_1 - z_0)\cdot(z_2 - z_0) < 0 \qquad (5)$$

$$(p_1 - p_0)\cdot(p_3 - p_0) < 0 \qquad (6)$$

$$(z_1 - z_0)\cdot(z_3 - z_0) > 0 \qquad (7)$$

$$(p_1 - p_0)\cdot(p_4 - p_0) < 0 \qquad (8)$$

$$(z_1 - z_0)\cdot(z_4 - z_0) < 0 \qquad (9)$$

iii) If for each point 1 (for each group) there are various possible points 2, 3 or 4, the points that minimise the following expression are chosen:

$$d_k^2 = \frac{(x_k - x_1)^2}{(x_{max} - x_{min})^2} + \frac{(y_k - y_1)^2}{(y_{max} - y_{min})^2} + \frac{(p_k - p_1)^2}{(p_{max} - p_{min})^2} \qquad k = 2,\ldots,4 \qquad (10)$$

where distances are divided into the maximum distance in order to avoid scale effect. A maximum d_k is also imposed.

The first condition is only a filter to select the points of A nearer to the iso-line. By using only this condition, an operations map could be built; but if δ values were small, the map would have very few points; and if δ values were high, the map's clarity would decrease. Hence, a more elaborated method is proposed.

The second and third conditions are used to build the four-point groups from the points that have passed the first condition filter. The second condition is proposed to ensure a good distribution of the four points around the unknown point. Since the surface $p = p_0$ and the plane $z = z_0$ determine the four regions in the space, each point of the group should be in a different region. Due to the third condition, the four points are in a small region in which the z function can be considered as linear (*Figure 4*). It should be noted that each point of **A** may either belong to none, one or more groups of four points.

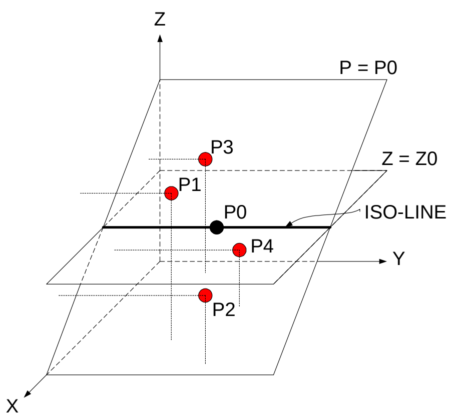


Figure 4. Scheme of the methodology.

Once the four-point groups have been built, the pairs (x_0, y_0) are generated (one pair from each group). To obtain these pairs, the dependent variable is expressed in each of the four points with a first order Taylor series around the point (x_0, y_0, p_0).

$$z_k = z_0 + z_x\left(x_k - x_0\right) + z_y\left(y_k - y_0\right) + z_p\left(p_k - p_0\right) \qquad k = 1,\ldots,4 \tag{11}$$

As there are four equations and five unknown quantities (z_x, z_y, z_p, x_0 and y_0), an additional condition must be added. This condition is that the following expression (distance from the new point to the old ones) should be a minimum:

$$d^2 = \sum_{k=1}^{4}\left(\frac{\left(x_k - x_0\right)^2}{\left(x_{max} - x_{min}\right)^2} + \frac{\left(y_k - y_0\right)^2}{\left(y_{max} - y_{min}\right)^2}\right) \tag{12}$$

By solving the five conditions imposed in equations (11) and (12), the coordinates for the point of B that is obtained from a group of four points of A are obtained. If this is done for each four-point group, all the points in B can be calculated. These points, when plotted, form the iso-line. It should be noted that this methodology uses the linear approach only locally (due to conditions 2 to 10) so that it can be used for any curved shape although it is based on the first order Taylor series.

5. Gasifier Operations Map from Plant Data

The methodology described above has been applied to the construction of an operations map of the gasifier for a 90% load (p=90). The plant data are the same that were used to validate the models. Since the iso-lines are now groups of points, it is more convenient to use one graph for each dependent variable. The graph that can be seen most clearly is that for the concentration of CO_2 (*Figure 5*).

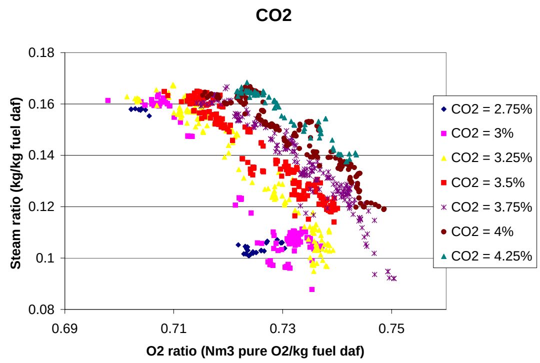


Figure 5. CO_2 operations map.

Operations maps show the same tendency as model-built maps, but they are limited to a more reduced zone. In this zone, both models give similar values, which explain why errors are reduced. The graphs of the other dependent variables are not as clear as the graph of CO_2 but, with the exception of the graph for H_2, the trends can be clearly seen. All the maps can be found in (Usón, 2002).

To improve the resolution of the graphs for the compositions, information about the fuel composition should be included. One way to do this is to apply the method to build the maps not based on the oxygen and steam ratios but on the ratios O/C and H/O that are calculated by dividing the total amount of carbon, hydrogen, and oxygen (taking into account the carbon, oxygen, and hydrogen contained in fuel, the steam, and the oxygen). Then, the pairs (x_0, y_0) should be transformed from O/C and H/O to oxygen/fuel and steam/fuel ratios by using an average fuel composition. This idea is based on the fact that, since the fuel conversion and final equilibrium constants are roughly constant and the influence of nitrogen and sulphur can be neglected, the final gas composition only depends on the relations between carbon, oxygen, and hydrogen. As can be seen in *Figures 6* and *7*, the graph of CO_2 becomes clearer and the graph of H_2 shows a trend (while when the steam and oxygen ratios were used directly, no trend was seen). The improvement obtained in the H_2 is due to the small molecular mass of this element which makes a small change in the fuel composition cause an important dispersion in the gas composition.

This problem might also be solved by making operations maps for the different kinds of fuels. However, our problem is not that there are several fuels but rather a continuous variation of fuel composition.

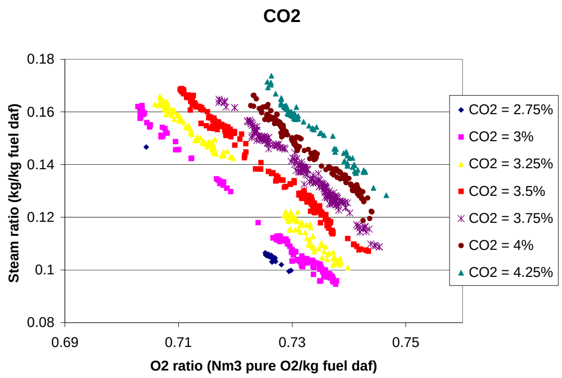


Figure 6. CO_2 operations map using ratio transformation and average fuel composition.

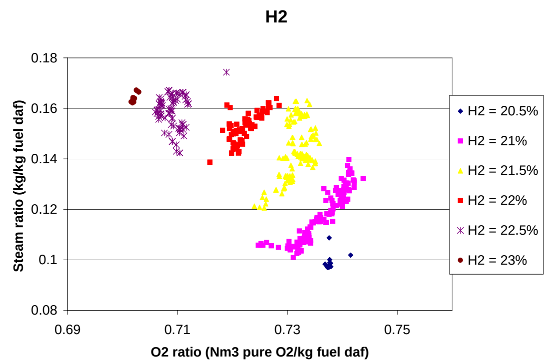


Figure 7. H_2 operations map using ratio transformation and average fuel composition.

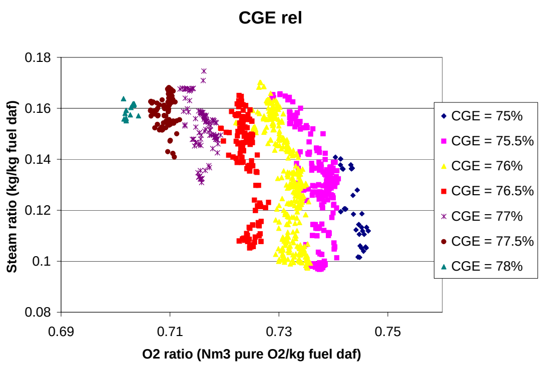


Figure 8. Relative CGE operations map using ratio transformation and average fuel composition.

Although the use of O/C and H/O ratios improves the clarity of the composition maps, this transformation is not suitable for energy related variables (temperature and CGE) because it mixes all sources of carbon, oxygen, and hydrogen without taking into account the variation of LHV that a modification of fuel composition implies. One way to introduce fuel LHV and use O/C and H/O ratios in the CGE map is to represent not CGE but a relative CGE (Usón 2002). This variable is calculated by introducing a correction factor f_{CGE} that allows one to take into account variations in the relation of fuel LHV and carbon content in the fuel:

$$CGE = CGE_{rel} \cdot f_{CGE} \tag{13}$$

$$f_{CGE} = \frac{38{,}500}{\left(\frac{LHV_{fuel}}{C_{fuel}}\right)_{(kJ/kg)}} \tag{14}$$

For the analysed periods, this factor varies from 0.982 to 1.015. In *Figure 8*, an operations map of CGE_{rel}, built by using O/C and H/O ratios, is shown. The iso-lines show that the gasifier is operated in the high fuel conversion zone by using oxygen ratios above the maximum CGE point.

The plant data operations maps presented in this section show the same tendencies as model-built operations maps but the iso-lines are slightly displaced. For example, the maximum CGE point would be displaced towards the left side of the plant data operations maps, while in the variable-conversion model operations map this point is near the centre. This aspect demonstrates that it has been very useful to build these maps from plant data. However, if these maps are to be used by plant operators, point families should be transformed into lines and all variables should be plotted on the same graph (*Figure 9*).

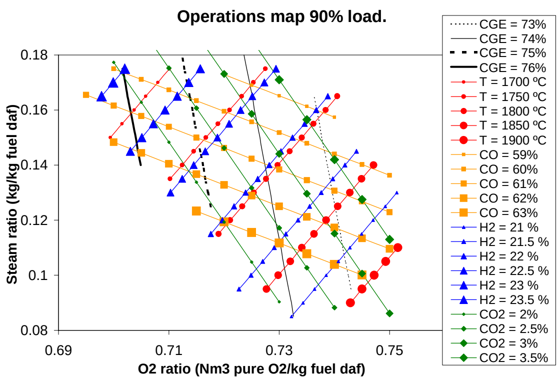


Figure 9. Operations map for operator use.

6. Conclusions

Since the gasifier runs with a high and constant fuel conversion ratio and variations of this parameters cannot be detected, a simple model like the one proposed by Van der Burgt is enough to reconcile plant data. However, if a wider operating range is explored, a more sophisticated model with variable fuel conversion ratio is needed.

An operations map is a practical tool, which can help one to understand how the gasifier works and how to efficiently operate it. By comparing the two model-built maps, constant conversion model limitations can be seen. Furthermore, although the models are useful for tuning the control system and for analysing new operating zones, it is better to build maps from plant data in order to study actual gasifier operation. Hence a new method was proposed, which is a general methodology that has three advantages: 1) it allows introduction of more than one independent variable; 2) it is not limited to any single type of graph (linear, polynomial); and 3) it can be applied to real operating periods because it does not even need distributed data. Thus, it can be very useful for studying any system.

The operations maps shown in this paper are currently being used in the Puertollano power plant for daily operations. Thanks to this work, operators have a graph in which the consequences of their actions are clearly plotted and can, thus, avoid errors and plant failures. Since plant data maps show that in normal operation the CGE can vary about 3 points, (about 5 MWe), the use of the maps can improve plant efficiency significantly.

6.1 Additional conclusions on the methodology

If coal is to play an important role as an abundant and even distributed energy source in the XXIst century, clean and efficient technologies must be used. Perhaps the most promising technique is gasification, because it allows one to enter the hydrogen society and facilitates the capture and disposal of CO_2 . However, gasification is not combustion. The optimum working condition of a gasifier is only obtained through the control of the reactive agents taking place in the reaction chamber (concentration, pressure and temperature), in opposition to combustion, which is a totally developed reaction.

Accordingly, the problem of obtaining operations maps is a universal problem that every existing or planned gasification plant will have to face. This problem cannot be solved by simply using a purely theoretical analysis but instead requires empirical feedback that helps solve the fine-tuning of a gasifier. As has already been stated, this could presume a loss in gasifier efficiency of as much as 3 percent. Therefore, the methodology developed in this paper can be of use for new IGCC plants provided that the experience gained from an already existing plant is considered.

Thus, the methodology presented in this paper can be summarised as follows:

i) Previously, it would have been necessary to have an on-line system that provided information about gasifier efficiency, pressures, temperatures and so on. This type of approach is common nowadays.

ii) As an alternative, a theoretical analysis can be carried out by using a model in order to obtain trends. The model should then be tuned by using plant data. Steam and oxygen ratios should be considered as independent variables and temperature, the main gas component concentrations and efficiency as dependent variables. An operations map should be used to plot all dependencies in a single graph.

iii) Operations maps from plant data should be built by using the method proposed in this paper. If these maps do not show the same trends as the model-built ones, the hypothesis assumed in the model should be revised.

iv) Finally, conclusions about how to modify operations to increase efficiency can now be obtained and a clearer version of the maps (converting the points to lines) provided to operators.

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Nomenclature

A	Initial group of points
B	Final group of points
C	Carbon content in the fuel
CGE	Cold gas efficiency [%]
d	Distance
daf	Dry and ash free

i	Real operating point
j	Point in an iso-line
k	Point in a four-point group
LHV	Lower heating value [kJ/kg]
max	Maximum
min	Minimum
p	Parameter
rel	Relative
x	Independent variable
y	Independent variable
z	Dependent variable
0	Coordinate of a point in an iso-line
δ	Increment

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