ChemPlant Technology s.r.o.

Report CPT- 440-21

Date of issue: 6.10. 2021

This report has 24 pages.

CPT

Heat Rate Analysis by RECON

Coal Fired Power Plants

Authors: Vít Madron

Leo Štěpán

Ústí nad Labem   October 2021

HISTORY OF REVISIONS

Revision No	Date	Description	Elaborated by	Approved by

CONTENTS

GLOSSARY AND ABBREVIATIONS

BMCR   Boiler Maximum Continuous Rating
CC   Cost of the Coal [MU/h]
CP   Coal Price [MU/kg]
CS   Corrected State
CV   Control Variables
CW   Cooling Water
CWT   Cooling Water Temperature
DD   Design Data
DR   Data Reconciliation. (1) Statistical correction of redundant measured
            variables to obey model equations. (2) Calculation of unknown variables
            from the reconciled ones.
DRV   Data Reconciliation and Validation. DR combined with data Validation
EBD   Energy Balance Diagram
EV   External Variable
GCV   Gross Combustion Value (synonymous with HHV)
HHV   Higher Heating Value (synonymous with GCV)
HR   Heat Rate
HTC   Heat Transfer Coefficient
IEE   IsEntropic Efficiency of a steam turbine
KPI   Key Performance Indicator
MU   Money Unit
OS   Operational State
PRIMADO   Process Industry Monitoring, Analysis, Diagnostics and Optimization
PC   Pressure in the Condenser
PP   Power Plant
PS   Parametric Sensitivity
RECON   Mass, energy and momentum balancing SW with Data Reconciliation and
            Validation
RS   Reference State
TMCR   Turbine Maximum Continuous Rating

1. INTRODUCTION

Heat Rate monitoring and analysis is the important part of PRIMADO which means Process Industry Analysis, Diagnostics and Optimization. PRIMADO is based on comparison of a Power Plant (PP) functioning in the **Operational State (OS)** with functioning in some **Reference State (RS)**. Such comparison can reveal differences in the equipment state (for example fouling of heat transfer areas in time or leaks in some parts of the PP) or differences caused by values of external or control variables of the PP. The RS is frequently the Design state but it can be also the state after a revamp or similar important action (data from the Performance test or typical data when PRIMADO was started and tested). For simplicity we will further use sometimes Design as the synonym for RS. Every of these two states (OS and RS) have usually two different sets of process variables:

1. Variables recorded at the RS (constants)
2. Actual variables of the OS (dynamic values)

These two states can be compared via Key Performance Indicators (KPI) of which the Heat Rate (HR) of the overall PP is the most important. This KPI has the direct link to the Power Plant economy. This information can be complemented also by the Steam cycle HR, by the Boiler's efficiency and by characteristics of individual PP components like turbines or heat exchangers. In other words, real (validated) process data, which are results of data processing, are compared with values at the RS. Further on we will concentrate on classical coal fired Power Plants but the methodology is also applicable to other types of thermal PPs.

The approach to the HR analysis is based on the philosophy described in the pioneering book "*Power Plant Performance Monitoring*" [1]. In comparison with this monograph we use systematically mathematical models based on process data (Process Data Driven Simulation). We don't rely on correction coefficient and curves provided by equipment vendors. Attention is paid to Data Validation and Reconciliation in the sense of another book "*Process Plant Performance. Measurement and data processing for optimization and retrofits*" [2].

2. PROBLEM STATEMENT

It is not possible to compare real process data and reference data directly. There is no sense in **direct** comparing of two states of a PP which differ for example in the load, coal grade, cooling water temperature, etc.

One solution of this problem is the **Correction** of OS to the RS condition**.** The comparison of the corrected OS with RS is typical for plant performance tests in the case of a new plant's commissioning or after plant's retrofitting (comparison of plant's parameters with the vendor guarantees).

The other possibility is the comparison of plant's OS with the RS by **Expectation** (Prediction) of the plant behavior based on extrapolation from the RS to operating conditions.

The situation is depicted in the next table. Recall that the state of an operating plant has 2 dimensions (the philosophy is based on the book [1] but it is further expanded by possibilities given by Data reconciliation and Data Driven Simulation by RECON):

- dimension of the state of Equipment
- dimension of values of process variables

Table 2.1: The Equipment state – Process Variables Matrix

Values of **Process variables**

		Reference State	Operational State
Equipment state	**Reference**	Reference (rated) performance (1)	Expected performance (2)
	Operational	Corrected operational performance (3)	Operational performance (4)

There are four states which are characterized by **two states of equipment** and by **two states of process variables**.

Both, Correction and Expectation can be done in practice by

- Correction curves (provided by equipment vendors)
- Correction coefficients (provided by equipment vendors)
- **calculations using physical modeling based on real plant data**.

We will now focus on the last possibility.

Example:

Let's suppose that the only difference between RS and OS is the cooling water temperature CW_T and the only KPI is the Heat Rate (HR). The Correction and Expectation steps are shown in the next figure:
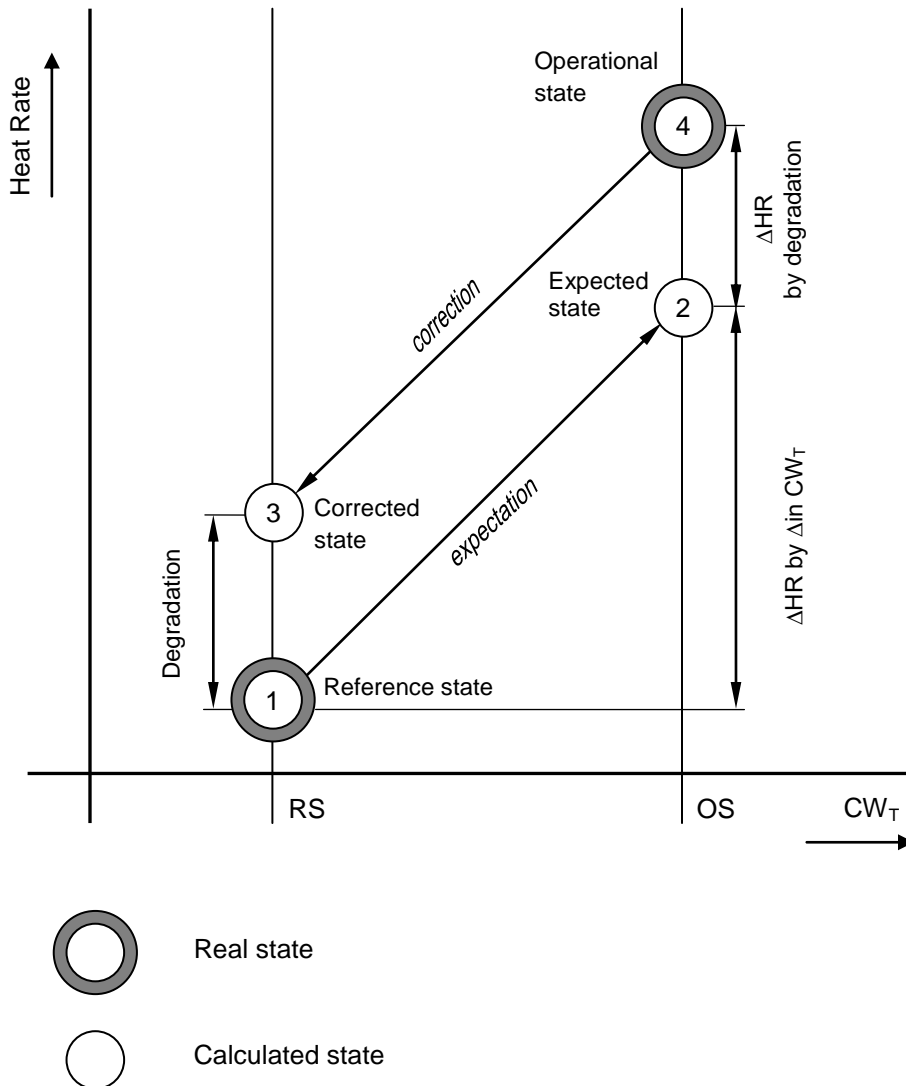
Fig. 2.1: Correction and Expectation (compare with Table 2.1)

In this case the real cooling water temperature is higher than in the RS which causes increase of HR from the state (1) to the state (2). This is our Expectation of plant's functioning under real operating conditions. Similarly, in the case of the Correction – the state (4) is corrected to the state (3). Notice that the difference (3) – (1) is one number while the difference (4) – (2) is a dynamic value depending on the real cooling water temperature.

Note: Instead of "Expectation" used in [1] we can meet sometimes the term "Prediction". These two terms are synonymous in what will follow.

The comparison of states (3) and (1) is the basis of **Monitoring Equipment Degradation.** The Degradation is characterized by one number independent on the PP operation state.

The comparison of states (4) - (2) and (2) – (1) can be the basis of **Monitoring Plant Performance.**

3. PROCESS VARIABLES

Variables playing role in the problem belong to 3 groups depending on whether operators can change them or not:

1. **External variables** that can't be changed by operators
2. **Control variables** which can be changed by operators
3. **Output variables** which are results of variables in preceding two groups.

3.1 External variables

External Variables (EV) which can't be changed by operators. The most important EVs are:

- Coal quality (GCV, ultimate analysis)
- PP load (required output electric power)
- Ambient air temperature
- Ambient air humidity
- Cooling Water temperature

Table 3.1: Influence of main External Variables on the PP Heat Rate

	Boiler Efficiency	Steam Cycle HR
Coal quality	Yes	No
PP load	Yes	Yes
Ambient air temperature	Yes	No
Ambient air humidity	Yes	No
Cooling water temperature	No	Yes

Note: Here we for simplicity suppose that the CW temperature is independent external variable. This holds for external CW sources like rivers or seas. In practice are more common circulating water systems based on Cooling Towers. Such systems are more complex and a resulting CW temperature is mainly a result of external conditions (ambient air temperature and humidity) and also can be influenced in the lesser extent by operators for example by the CW flowrate. If required, the CW system model can be integrated with the rest of the PP model. In such case the CW temperature is the Output of the model and not the EV.

3.2 Control (controllable) variables

Control variables which can be changed by operators, at least in some extent. Examples can be the main steam temperature and pressure, reheat temperature,

cooling water flowrate, etc. Improper values of control variables cause so called **controllable losses.**

3.3   Outputs

The rest of variables depend on values of EVs and CVs. These variables will be called further **Outputs** (many state variables inside the PP like flowrates, temperatures and pressures). Among Outputs belong also KPIs, namely efficiencies, heat rates and others.

All this has analogy with solving systems of equations of the process model. EVs and CVs are Input variables and Outputs are results of solving the system of equation.

3.4   **What are Design (Reference) Data?**

- The main Design Data (DD) belong to two areas of the PP:
    - Boiler and its accessories (air preheat system, mills, fans)
    - Steam Cycle (SC) including steam turbines, alternator, condenser, pumps, feed water preheat system etc.
- DD provided by PP vendors are in the form of mass and energy balance tables or flowsheets characterized by several main variables:
    - the **Load** expressed usually as % of TMCR or BMCR (important both for the Boiler and the SC)
    - for the Boiler there can be **several grades of coal**
    - some variables are not independent (for example the main steam pressure in the Sliding pressure regime depends on the load)
    - the other variables in DD are usually supposed to be constant (temperature of ambient air, temperature of the cooling water, etc.)

- In what follows in this document we will suppose that DD depends on the Load only (independent variable) and the Sliding Main steam Pressure is a function of it taken from the Design.

DD is needed for presentation of PRIMADO results. They must be extracted from PP documentation and must be available in the form of regression functions or of tables which can be interpolated.
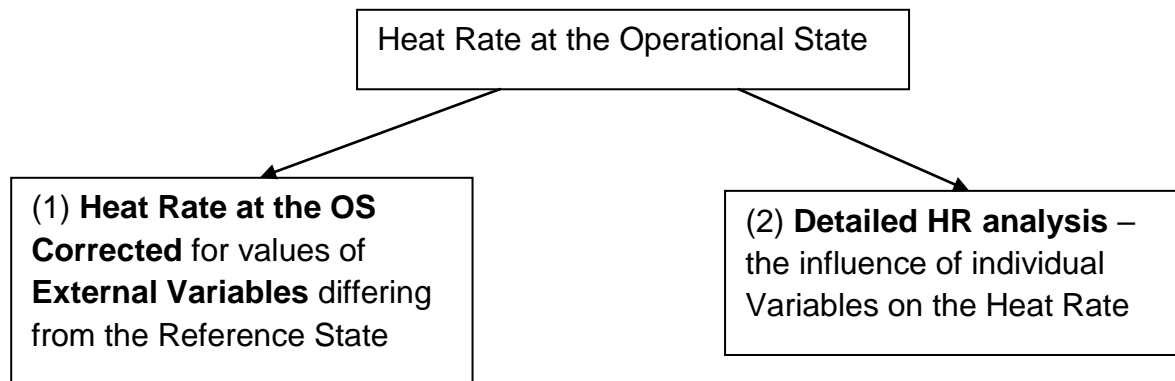
Note: If the Reference State is not the Design, Reference Data can be extracted for example from the State after a revamp or the State when the PRIMADO methodology was implemented.

4. HEAT RATE ANALYSIS BY RECON

4.1   Introduction

Recall that the main problem is: It is not possible to compare real operational data with DD directly because there are other independent variables which are different in real operational data and DD (for example, the main steam temperature which is the Controllable variable or the cooling water temperature which is the External variable). Further on we will concentrate on the Heat Rate analysis. There can be many ways how to present Heat Rate analysis to users. In the next will be described the following **two step method**:

1. Correction of HR for External Variables
2. Detailed analysis of HR for individual Control Variables

```
                    ┌─────────────────────────────────────┐
                    │  Heat Rate at the Operational State  │
                    └─────────────────────────────────────┘
                         ↙                           ↘
┌──────────────────────────────────┐     ┌─────────────────────────────────┐
│ (1) Heat Rate at the OS          │     │ (2) Detailed HR analysis –      │
│ Corrected for values of          │     │ the influence of individual     │
│ External Variables differing     │     │ Variables on the Heat Rate      │
│ from the Reference State         │     │                                 │
└──────────────────────────────────┘     └─────────────────────────────────┘
```

The Total (Gross) difference $HR_{OS} - HR_{RS}$ consists of 3 parts:

ΔHR_{EV} HR difference due to External Variables

ΔHR_{CV} HR difference due to Control Variables

ΔHR_{Degrad} HR difference caused by the equipment degradation **which includes also some unexplained influences**.

$$\Delta HR_{Total} = HR_{OS} - HR_{RS} = \Delta HR_{EV} + \Delta HR_{CV} + \Delta HR_{Degrad} \qquad (4\text{-}1a)$$

After the correction made in the first step the influence of the External Variables ΔHR_{EV} is filtered of.

The difference ΔHR_{CV} is the sum of HR differences caused by all Control Variables differing from the RS.

ΔHR_{Degrad} is then calculated from Eq. (4-1a)

$$\Delta HR_{Degrad} = \Delta HR_{Total} - \Delta HR_{EV} - \Delta HR_{CV} \qquad\qquad (4\text{-}1b)$$

Note: After the startup of the PP operation it is frequently possible to observe improvement of PP's efficiency due to the well known "Learning Curve". It can happen that because of uncertainties in the design parameters and similar effects ΔHR_{Degrad} can be negative for some time.

4.2 Basic terms and methods

HR [kJ/kWh] is defined as the ratio of the heat input to the system and the power generated by the system. For the coal fired power plants HR rate can be calculated from the formula (this holds also for other fossil fuels PPs).

$$HR_{PP} = \frac{F_{coal}*HHV}{P} \qquad\qquad (4\text{-}2)$$

HR_{PP} is   the power plant HR [kJ/kWh]
F_{coal} coal input [kg/h]
HHV Higher Heating Value of the coal [kJ/kg]
P power plant's electricity generator power [kWh/h]

Note: This is so called Gross HR. In the case of the Net HR the electricity needed for running the Power Plant is deduced from the power generated. Further we will deal with the Gross HR only. The modification to the Net HR is easy.

Similarly can be defined also the HR of the Steam Cycle:

$$HR_{SC} = \frac{E}{P} \qquad\qquad (4\text{-}3)$$

where

HR_{SC} is   the Steam Cycle HR [kJ/kWh]
E heat energy provided to the SC by the boiler [kJ/h]
P power plant's electricity generator power [kWh/h]

The third characteristic of the PP is the Fuel Boiler Efficiency. It is defined as the useful heat generated by the boiler divided by the coal energy input (the Fuel Efficiency defined in [5]):

$$\eta_B = \frac{E}{F_{coal}*HHV}$$ (4-4)

where

η_B is   Boiler Fuel Efficiency [5]
E   heat energy provided to the SC by the boiler [kJ/h]

Note: Efficiency can be also expressed in per cents.

Between these three power plant's characteristics holds the following relation:

$$HR_{PP} = \frac{HR_{SC}}{\eta_B}$$ (4-5)

The cost of coal needed for electricity generation can be calculated with the aid of Eq. (4-2):

$$C_C = \frac{HR_{PP}*P*C_P}{HHV}$$ (4-6)

where

C_C is   coal cost [MU/h]
C_P coal price [MU/kg]

HR_{PP} can be expressed in terms of the boiler efficiency and the SC HR - see Eqs. (4-5) and (4-6). For C_C then holds:

$$C_C = \frac{HR_{SC}*P*C_P}{\eta_B*HHV}$$ (4-7)

Sometimes it is required to quantify the relative influence of the boiler and the SC on the overall power plant HR and the coal cost. This relation can be derived from Eq. (4-7). Let's suppose that HR_{SC} and η_B has changed from some standard values by Δ. The coal cost function (4-7) can be linearized to the form

$$\Delta C_C = \frac{\partial C_C}{\partial HR_{SC}} \Delta HR_{SC} + \frac{\partial C_C}{\partial \eta_B} \Delta \eta_B = \frac{P*C_P}{HHV*\eta_B} \Delta HR_{SC} - \frac{HR_{SC}*P*C_P}{HHV*\eta_B^2} \Delta \eta_B \qquad (4\text{-}8)$$

where Δ means the increment of a given variable. The two expressions on the right hand side of Eq.(4-8) represent shares of the steam cycle and of the boiler on the overall change of the coal cost ΔC_C. The similar equation holds also for the Heat Rate:

$$\Delta HR_{PP} = \frac{\partial HR_{PP}}{\partial HR_{SC}} \Delta HR_{SC} + \frac{\partial HR_{PP}}{\partial \eta_B} \Delta \eta_B = \frac{1}{\eta_B} \Delta HR_{SC} - \frac{HR_{SC}}{\eta_B^2} \Delta \eta_B \qquad (4\text{-}9)$$

4.3   HR modeling by simulation

HR modeling means studying the influence of process variables on the HR. This can be done in 2 steps:

1. Identification of model parameters from operational process data. Process data are imported from the data source and the DVR data processing with the model for DVR is executed. Outputs of calculation are model parameters.
2. The next step is the modifying values of one or more input variables which are the new Input of calculation. Calculation is done with the Simulation model. The Simulation model differs from the DVR model by classification of variables as Measured, Fixed or Nonmeasured. The second difference is that the Simulation model has no data redundancy. It is just the solution of the system of equations.

The typical place of using this method is the What if? module of the RECON or the HR correction for External Variables.

4.4   HR modeling by Parametric Sensitivities

Sometimes it is required to gain the information about the influence of many process variables on one or more KPIs. Making repeated simulations for all of required process variables can be time prohibitive. This is for example typical for creation of operators' screens. The solution can be based on using Parametric Sensitivities (PS). It should be noted here that this approach can be applied only to simulation models without redundancy.

PS is a well-known concept in the domain of mathematical modeling. With some simplification, it can be formulated as the question:

What is the change in the result of computation with unit change in the parameter value?

In the common simulation calculations the situation is relatively straightforward. If the model is linear, the parametric sensitivity can be found easily and exactly. With nonlinear models, we find an approximate solution via the linearization of the model by Taylor series development. Let's suppose that the HR depends on measured variables x_i. For the *HR* such equation is:

$$HR = HR(\boldsymbol{x}) \cong HR(\boldsymbol{x}) + \Sigma \frac{\partial HR(\boldsymbol{x})}{\partial xi} \, \Delta x_i \qquad (4\text{-}10)$$

The partial derivatives $\partial HR(\boldsymbol{x})/\partial x_i$ are PS of *HR* on variables x_i. For the increment Δ of *HR* caused by the increment of x_i then holds

$$\Delta HR = \frac{\partial HR(\boldsymbol{x})}{\partial xi} \Delta x_i \qquad (4\text{-}11)$$

This approach solves the PS of HR on calculation inputs, i.e. Measured and Fixed variables. Also don't forget that the model must be without redundancy (simulation model).

The problematic queries

Sometimes we can meet the requirement of HR Parametric Sensitivities on an uNmeasured variable. As an example can serve the condenser pressure (PC). While it is usually measured, in the simulation mode it is classified as unmeasured. It is the function of many other variables (CW temperature, condenser fouling, the load, etc.). So, the query *"What is the PS of HR on the PC?"* is **not well posed**. The condenser pressure is the typically secondary variable which is the result of many other variables. It is not possible to find the answer without the information which primary variable is the cause of the *PC* change.

The solution can be based on specifying the primary cause of the *PC* change. The good query can be "*What is the PS of HR on the PC if the change of PC is caused by the CW temperature change?"*.

This query formulation can be solved in the *What if?* module of RECON. This needs to make the perturbation of the CWT and to see the increments of the HR and the PC. The ratio *ΔHR and ΔCP* is the answer. The same approach can be applied also in the case of Parametric Sensitivities.

$$\frac{\partial HR}{\partial PC} = \frac{\partial HR/\partial CWT}{\partial PC/\partial CWT} \tag{4-12}$$

The parametric sensitivity of HR is thus the ratio of two other PSs. Anyway, it should be noted that this holds for the HR change caused by CWT only.

4.5   Correction of HR for External Variables

The purpose of this step (recall introduction of the Section 4.1) is to filter off the influence of the difference between the OS and the RS caused by differences in External variables. In this step **the correction concerns External variables only**. The typical selection of such variables is presented in the next table:

Table 4.1: Typical External Variables used for a PP Heat Rate correction

No	Variable	Unit
1	Ambient air temperature	^{o}C
2	Ambient air humidity	%
3	Cooling water temperature	^{o}C
4	Coal HHV	kJ/kg
5	Coal Ash	%
6	Coal moisture	%
7	Coal Carbon	%
8	Coal Hydrogen	%
9	Coal Oxygen	%
10	Coal Nitrogen	%
11	Coal Sulfur	%

Note 1: The influence of air humidity on the boiler efficiency is only marginal but not negligible. For example in one Case Study, at 27 ^{o}C the increase of the relative air humidity from 60 % to 100 % means decreasing the boiler efficiency by ca 0.12 % and the PP HR is increased by 11.3 kJ/kWh (0.14 %).

Note 2: Variables No. 4 – 11 in Tab.4.1 should be understood as one complex variable. It is not wise to study the influence of individual items separately.

The best way of calculating the HR difference between the Operational and Reference States is the **simulation.** HR at the OS is known from the previous DVR calculation

step. Then the simulation model is used with External Variables' values from the Reference State while the remaining variables have their values from the OS (compare with Fig. 2.1).

Note 1: Using the Parametric Sensitivities method in this case would be difficult due to the complex character of the coal quality.

The presentation of results can be done by the following table:

Table 4.2: Results of correction for External variables

UNIT HEAT RATE	ACTUAL	CORRECTED	ACTUAL-CORR.	GAIN/LOSS
GROSS UNIT HR				
GROSS TURBINE HR				
GROSS BOILER EFFIC				

4.6 Detailed analysis of HR for Controllable Variables

In the previous section we have shown how the influence of External Variables on the HR was filtered off. The next step is showing details – losses/gains caused by values of individual Control Variables differing from the Reference State. Typical variables of this kind are in the next table:

Table 4.3: Typical Controllable Variables used for a PP Heat Rate **detailed analysis**

No	Variable	Unit
1	Main steam temperature	^{o}C
2	Main steam pressure	MPa
3	Reheat steam temperature	^{o}C
4	O2 concentration in FG exiting Economizer	vol %

Results of this step can be presented via the following table:

Table 4.4: Results of HR$_{PP}$ correction for Controllable Variables

VARIABLE	ACTUAL	DESIGN	DEV.A-D.	HR DEV.	GAIN/LOSS
MAIN STEAM TEMP.[^{o}C]					
MAIN STEAM PRESS.[kPa]					
RH STEAM TEMP. [^{o}C]					
O2 ECO EXIT [vol.%]					
TOTAL	-	-	-		

Solution of monitoring the influence of all possible influencing variables by simulation calculations (one simulation for one CV) can be time prohibitive. This obstacle can be overcome by combination of the simulation and using on line calculated Parametric Sensitivities. This method is based on linearization of model equations in the point of validated process data. Typical models in the power industries are not far from linearity and an error caused by linearization is typically less than the intrinsic model error. The parametric sensitivities technology is thus suitable especially for providing information in screens available for operators where the time needed for simulation of all possible variants is time prohibitive.

The calculation process is as follows:

1. DVR data processing
2. Running the simulation model calculating Parametric Sensitivities which are saved in the historical database
3. Reading Parametric Sensitivities from the database and filling Table 4.4.

If someone requires the rigorous simulation for comparison, he can visit the What if? Queries module.


4.7   Example

We recommend the reader to revisit Chapter 2, Fig. 2.1. Now we will apply the Correction of the OS Heat Rate to the RS conditions for more than one variable. Let's suppose that there are only two independent variables:

- The External Variable (EV) T_{wcin} – Cooling water inlet temperature
- The Controllable Variable (CV) C_{O2} – concentration of the oxygen in the Flue Gas at the economizer outlet.

Let the **original Heat Rate** (the RS) is **8100 kJ/kWh** (e.g. the Design HR).

Let's further suppose that data is characterized by the following values shown in the Figure 4.1. Data were generated by simulation based on real plant data processed in the DVR step.
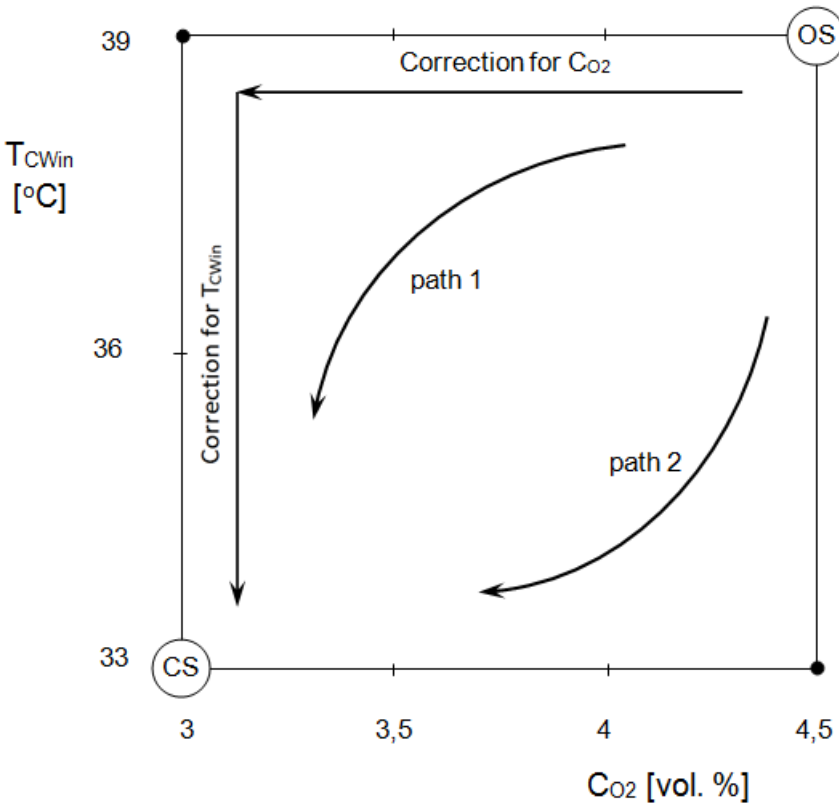
Fig. 4.1: Area for HR analysis. Heat Rate depends on the CW temperature and oxygen concentration at the economizer outlet.

Corrected State (**point CS**)

- O_2 3   [vol.%]
- T_{CWin} 33   [$^{\circ}$C]
- HR   8209.2 [kJ/kWh] (corrected HR)

Operating State (**point OS**) is

- O_2 4.5   [vol.%]
- T_{CWin} 39   [$^{\circ}$C]
- HR   8384.5 [kJ/kWh]

Note: This example serves for illustration of this subject. We talk for simplicity about losses caused by increased HR. In practice losses can be in some situations negative which means gain.

In the Fig. 4.1 is shown the two step correction procedure (path 1, correction for C_{O2} first and then correction for T_{CWin}) which will be used in most of this Example. The possibility to use the alternative Path 2 (correction for T_{CWin} first and then correction for C_{O2}) will be discussed at the end of this section.

In the next Fig. 4.2 is shown the two dimensional planar model of HR depending on both variables.
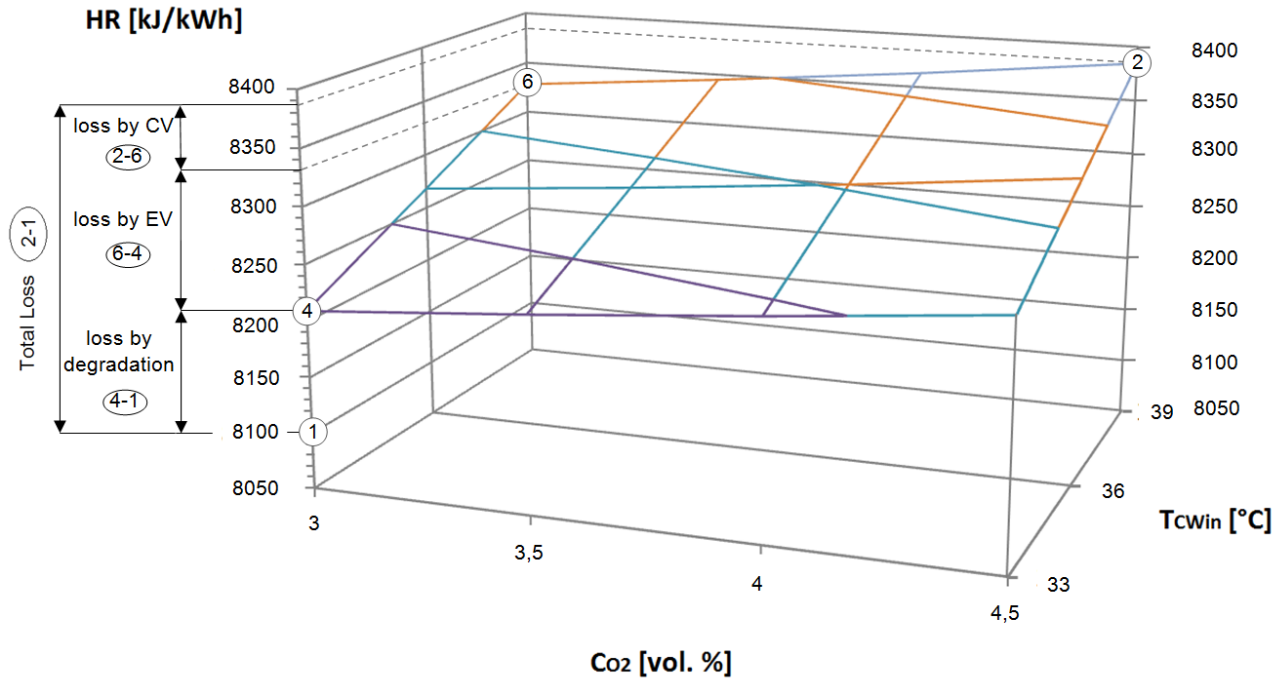
Fig. 4.2: Two dimensional graph of HR.

On the left hand side can be seen the **Total Loss** caused by the difference between the HR at the RS and HR at the OS. There are also shown other **Losses**.

Heat Rates are summarized in the next Table 4.5:

Tab. 4.5: Heat Rates for individual points in [kJ/kWh]. Numbers in () refer to the Row No in Tab.4.6. CS and OS heat rates are presented in the next table

$C_{O2} \rightarrow$ T_{CWin}	3 [vol.%]	4.5 [vol.%]
33 [°C]	(4)8209.2	8263.2
39 [°C]	(6)8328.2	(2)8384.5

We can now make a simple balance of individual losses calculated via HR changes

Tab. 4.6: Balance of individual losses caused by changes in HR

Row No.	Row operation	Variable	HR [kJ/kWh]
1		HR at Reference State (original HR)	8100
2		HR at OS	8384.5
3	2-1	**Total loss**	**284.5**
4		HR corrected for EV and CV (CS)	8209.2
5	4-1	**Loss by degradation**	**109.2**
6		HR corrected for CV (C_{O2})	8328.2
7	2-6	**Loss by CV (C_{O2})**	**56.3**
8	6-4	**Loss by EV (T_{CWin})**	**119.0**
9	5+7+8	**Sum of losses**	**284.5**
10	3-10	Difference of losses	0

We have already mentioned the possibility to use for the HR analysis also the Path 2 in Fig. 4.1 (to change order of corrections). It is clear that the sum of losses must be independent on the path. But such expectation does not hold for partial losses caused by individual variables (rows 7 and 8 in Table 6. Results are presented in Table 4.7.

Table 4.7: Comparison of individual losses for paths 1 and 2 [kJ/kWh]

Variable	Path 1	Path 2	Difference
Loss by T_{CWin}	119.0	121.3	-2.3
Loss by C_{O2}	56.3	54.0	2.3

What is the reason? Our considerations about HR hold exactly only for linear models of HR. Simply speaking, the overall loss caused by both variables (CV and EV) for nonlinear models is not exactly the sum of losses by both variables. For nonlinear models the influence of individual variables can't exactly distinguished. But differences in

Table 4.7 are marginal in comparison with the uncertainty of overall losses or the whole HR.

4.8   Operators' screens

HR Analysis can be clearly presented at following Screen – Fig. 4.3. All HR corrections and deviations are shown in separate tables for External and Internal Variables corrections and difference due to degradation and other variables. Gains and losses are coloured by different colours. Our Screen is taken from a real power plant performance so values don't match with our example in this chapter.
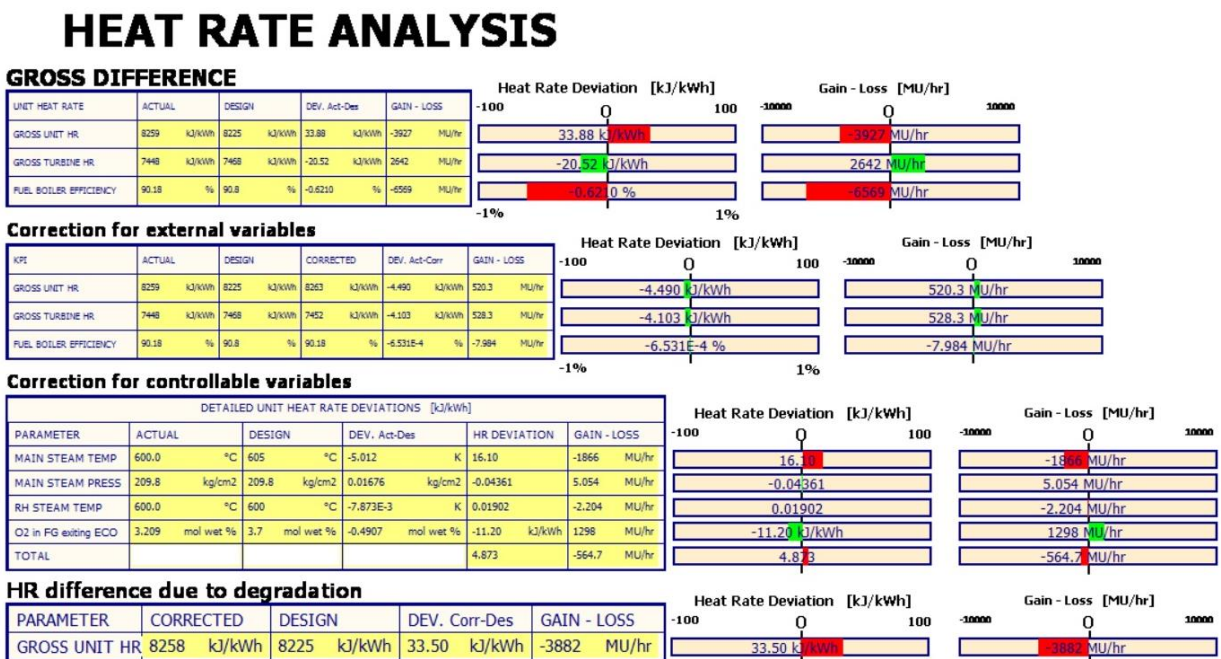

Fig. 4.3: Example of HR Analysis Screen.

4.9   HR presentation summary

The HR analysis can be presented by 4 tables:

1. Raw comparison of OS and RS

Table 4.8: Comparison of the ACTUAL and the DESIGN KPIs

UNIT HEAT RATE	ACTUAL	DESIGN	ACTUAL-DES.	GAIN/LOSS
GROSS UNIT HR				
GROSS TURBINE HR				
GROSS BOILER EFFIC				

2. Correction of OS for the difference in External Variables (Table 4.2)
3. Detailed analysis of losses caused by Control Variables (Table 4.4)
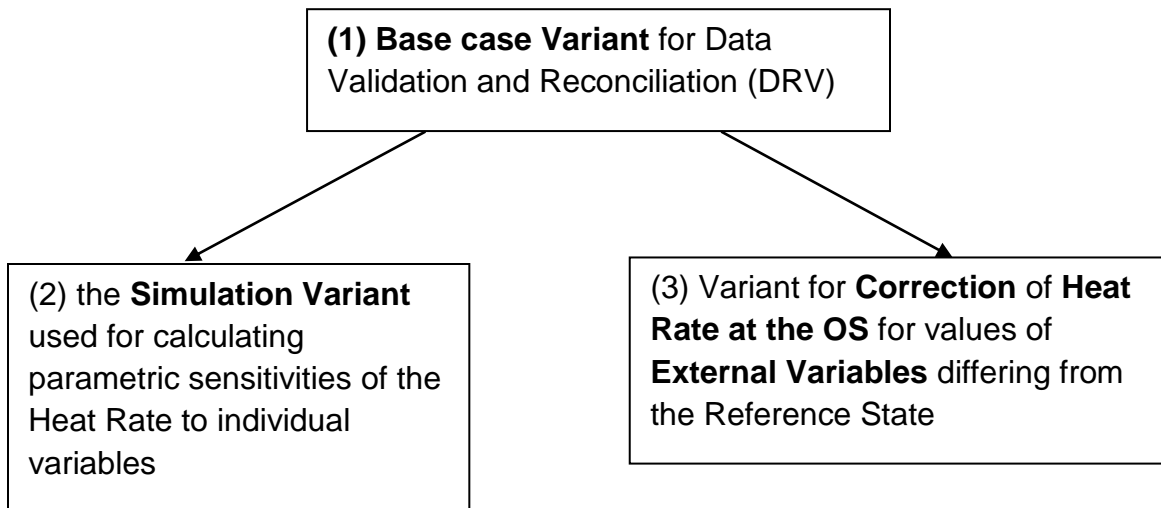4. Calculated overall Degradation according the Eq.(4-1b).

Steps 1 and 2 should include the Boiler efficiency and HR SC and HR PP. To make the presentation simple, it is sufficient to make the analysis for Gross efficiency and Gross HR only.

It is useful to make this analysis in thermodynamic variables (HRs and Boiler efficiency) and also in Money Units (the Cost of coal).

5. HOW IT WORKS?

The solution is based on one PP model which makes DVR (the Base Case) and 2 Variants (for more info about model Variants see Report [3] or the Appendix 1 below).

```
                    ┌─────────────────────────────────────┐
                    │ (1) Base case Variant for Data       │
                    │ Validation and Reconciliation (DRV)  │
                    └─────────────────────────────────────┘
                      ╱                               ╲
                     ╱                                 ╲
   ┌──────────────────────────────┐   ┌──────────────────────────────┐
   │ (2) the Simulation Variant   │   │ (3) Variant for Correction of │
   │ used for calculating         │   │ Heat Rate at the OS for values│
   │ parametric sensitivities of  │   │ of External Variables differing│
   │ the Heat Rate to individual  │   │ from the Reference State      │
   │ variables                    │   │                               │
   └──────────────────────────────┘   └──────────────────────────────┘
```

(1) The **Base Case Variant (#0)** serves for preparing validated data from the real plant data including model parameters like turbine efficiencies, etc. These data are saved in the database.

(2) From the Base Case Variant is created the **Simulation Variant** (#1) suitable for calculating **parametric sensitivities** of HR to individual variables. Model parameters needed for simulation are taken over from the preceding DVR step. Parametric sensitivities are saved in the MS SQL DB for further use in presentations, screens, etc. The Simulation model is identical with the model for What if? Queries

(3) The **Correction Variant** (#2) is used for calculating of the PP behavior under Design values of **External Variables**. In other words, the Simulation calculation is run with Designed values of External variables. Model parameters needed for simulation are taken over from the preceding DVR step (1). Corrected HR and other KPIs can be saved in the MS SQL DB for further use.

To summarize, the whole HR Analysis process requires 4 runs of RECON (two DVR steps and 2 Simulation steps). As the time needed for calculation of every step in few seconds, this method is applicable for on line use.

6. SUMMARY AND DISCUSSION

It was shown that data influencing PP economy belongs to 3 groups

- **External Variables** which operators can't influence (coal properties, ambient temperature, …). They can serve only for correction of the PP state to the design condition. The difference of KPIs between the real state and the corrected state represents just the distance of these two states. This difference is only informative for PP operators.

- **Control Variables** are variables which are in the scope of operators (main steam temperature, cooling water flowrate, …). These variables should be evaluated regularly and compared with the design. Operators should get info about differences between real and designed values including also the information about the impact of these differences on important KPIs.

- **Outputs of calculations** which include unmeasured process variables and also important KPIs (like HR). There are some important outputs which should be watched carefully. Some of them can be influenced by operators (for example the fouling heat transfer inside the boiler or the RAPH caused by soot sediments). The other uncommon values can signal problems which are out of operators' possibilities but are important for other PP's staff.

- **Losses** can be from the point of view of operators **Uncontrollable** (caused by External Variables) and **Controllable** (caused by Control Variables).

- **It is useful to discuss here the use of Design Data as the Standard State:** The Design state has never existed in practice. Moreover, after the PP was commissioned and accepted, it is too late to complain about differences between the Design and the operating new plant. These differences should be forgotten (in the future they would only cause misinterpreting of PRIMADO results). We are sure that the best Reference State for PRIMADO is one or few sufficiently long PP runs at stationary state with carefully checked and validated data. Such data should be carefully processed by the PRIMADO software and used as the new Reference State(s).

LITERATURE CITED

[1] Gay, R.R., Palmer, C.A. and Erbes, M.R.: *Power Plant Performance Monitoring*. Techniz Books International, New Delhi 2006

[2] Madron, F.: *Process Plant Performance. Measurement and data processing for optimization and retrofits.* Ellis Horwood, Chichester 1992

[3] *Calculation Variants in RECON*. Technical Report CPT 441–21, Usti nad Labem 2017

[4] *Process Plant Performance Monitoring and Analysis by Recon*. Technical Report CPT 375–17, Usti nad Labem 2017

[5] ASME PTC 4-2008 *Fired Steam Generators*: