

## Optimisation of an industrial afterburner

**Tomas Öberg** [info@tomasoberg.com](mailto:info@tomasoberg.com)

Tomas Öberg Konsult AB, G. Brov. 13, SE-371 60 Lyckeby, Sweden

### Abstract

An industrial afterburner was optimised using statistical experimental design. A computer generated optimal design was adapted to domain constraints and previous knowledge about the experimental variables. Carbon monoxide was used as a general indicator for the operating conditions and a reduced response surface model was fitted to the experimental data. In a second phase, the initial results were verified and investigated in more detail with regard to chlorinated aromatics. The empirical models obtained were further interpreted using results from laboratory investigations and more fundamental knowledge from combustion theory.

*Keywords:* Optimisation; Afterburner; Statistical experimental design; Response surface model; Linear regression

### Introduction

Afterburners are widely used in industry to control emissions of volatile organic compounds (VOC) from different manufacturing processes [1]. In an afterburner, combustible organic compounds are oxidised by raising the temperature of the material above its autoignition point in the presence of oxygen, and maintaining it at high temperature for sufficient time to achieve complete combustion to carbon dioxide and water. The residence time, turbulence and operating temperature are basic design factors that control the efficiency of all combustion processes.

The thermal decomposition characteristics of different organic compounds show a substantial variability, both under oxidative and pyrolytic conditions [2]. A good surrogate/indicator compound, with high thermal stability, can substantially facilitate investigations if it can be monitored continuously and at a reasonable cost. Carbon monoxide (CO) has a thermal stability that surpasses most organic compounds [3]. CO is also present in concentrations that allow the use of IR-based instruments for continuous measurements.

Statistical design of experiments has been used by industry since the 1940's in all type of experimentation. Computer-assisted experimentation is particularly useful in developing experimental plans for the situations when classical designs are not applicable, e.g. irregularly shaped experimental domains [4]. Atkinson and Donev give a more general discussion of the general theory of optimum design of experiments [5].

Response surface models are usually calculated from designed experiments using ordinary least squares fitting of the regression equations [6-7]. Passively recorded process data usually result in an ill-conditioned data matrix with highly co-linear variables and then bilinear regression techniques, like principal component regression (PCR) or partial least squares regression (PLSR), are better suited [8].

In Sweden, larger industrial operations listed as hazardous to the environment require a permit that is issued by a regional environmental court [9]. The Environmental Court in Stockholm has as one item of a recent permit decided that the steel manufacturer SSAB Tunnplåt AB shall investigate if the operation of two afterburners in the Borlänge steelworks can be optimised to further reduce emissions of environmentally hazardous compounds [10].

SSAB Tunnplåt AB is the biggest steel sheet manufacturer in Scandinavia and one of Europe's leaders in the development and manufacture of high-strength steel grades. Prepainted steel sheet is one major product produced in the Borlänge steelworks. The paint is applied to the steel sheet and the solvents are subsequently removed in a drying oven, where hot air (200-300 °C) is blown onto the sheet. Solvent rich off-gases from the drying oven are combusted in an afterburner fired with liquid petroleum gas (LPG). Parts of the flue gases from the afterburner are recirculated to control temperature in the drying oven and also used to preheat the off-gases before combustion.

The aim of this study was to investigate how changes in operating conditions affect the performance of the afterburner chamber No. 2 at SSAB Tunnplåt AB with regard to combustion efficiency and emissions of chlorinated aromatics. The study incorporates the use of multivariate data analysis and statistical design of experiments.

## **Experimental**

A preliminary screening analysis of passively recorded process measurement data, 15 operational variables, from the afterburner chamber was performed using PLS-regression. This screening analysis did not reveal any patterns or relationships that could be directly used to optimise the combustion process, and this is not to be expected either since the process is run with fixed set points. The next step was therefore to carry out a full-scale experimental study on the afterburner chamber operation.

Paints with different compositions are used in this plant, but chlorine-containing Platisol paint was selected for the purpose of carrying out this experimental study. Platisol is a suspension of fine granules of polyvinylchloride (PVC) in plasticizers.

Six operational parameters were initially selected as experimental variables for this study, table 1.

*Table 1*  
*Experimental variables.*

<b>Variable</b>	<b>Unit</b>	<b>Low level (-1)</b>	<b>High level (+1)</b>
A: Drying oven ventilation	ton/h	25	30
B: Coating plant line speed	m/min	30	60
C: Afterburner temperature	°C	675	750
D: Paint system		P100	P200
E: Steel sheet thickness	mm	0.55	1
F: Temperature curve in drying oven		Straight	Reversed

All possible combinations of these experimental variables are not feasible. The paint system P200 (Plastisol 200  $\mu\text{m}$ ) is only available for a steel sheet thickness of 0.55 mm, and a steel sheet thickness of 1 mm can only be produced with a line speed of 30 m/min. Ventilation, line speed and temperature are continuous variables, but it was only temperature that was feasible to vary between more than two levels. Standard factorial and/or response surface designs are not possible to apply within these constraints. In contrast, computer generated optimal designs is a viable alternative.

A list of candidate points for the experiments was prepared, including all possible combinations of the “high” and “low” levels for the first five variables and three different levels of afterburner temperature, in all 96 experimental settings. The normal operating set point was selected as intermediate level for the afterburner temperature. Candidate points violating the constraints were withdrawn, leaving 60 candidate points. A D-optimal design was generated for a model describing linear effects in all variables and quadratic effects for the afterburner temperature. 16 experiments were selected using the DETMAX algorithm [11]. Three replicates were added to the final design, table 2. All variables are coded  $-1$  -  $+1$ .

*Table 2*  
*Experimental design.*

<b>Run</b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>	<b>F</b>
1	1	-1	1	-1	-1	-1
2	-1	-1	1	-1	1	1
3	1	1	-1	-1	-1	-1
4	1	-1	-1	-1	1	1
5	-1	-1	-1	-1	1	-1
6	-1	-1	1	-1	-1	-1
7	1	-1	-1/3	-1	1	-1
8	-1	1	-1/3	-1	-1	1
9	-1	1	-1	-1	-1	1
10	1	-1	-1/3	-1	-1	1
11	-1	-1	1	-1	1	1
12	-1	-1	-1	1	-1	-1
13	-1	-1	-1/3	1	-1	1
14	-1	1	-1/3	1	-1	-1
15	1	-1	-1	1	-1	1
16	1	1	1	1	-1	-1
17	-1	1	-1/3	1	-1	-1
18	1	1	1	1	-1	1
19	-1	1	-1/3	1	-1	-1

The run order was not randomised with regard to the paint system since it was not feasible for the production to make intermediate changes. Each trial lasted for about 6 hours.

Verifying trials were carried out about 5 months after the first experimental study. Only the temperature was changed this time, keeping the other experimental variables constant with the following settings: Paint system P200, ventilation 30 ton/h, line speed 60 m/min, steel sheet 0.55 mm and a reversed temperature curve. Four trials were carried out, at 675, 700, 725 and 750 °C respectively. This time each trial lasted for about 4 hours.

Results from on-line sensors and gas instruments (CO, NO and O<sub>2</sub>) were recorded as 1-minute averages. An all-glass sampling equipment was used for collecting samples of chlorinated aromatics. The sampling and analytical procedures for halogenated aromatics in flue gases have been extensively described in an earlier paper [12]. The gas instruments were located immediately after the outlet from the afterburner chamber, while the sampling of chlorinated aromatics took place in the stack. A substantial amount of cooling air (approx. 40% of total gas flow) is added in the flue gas duct.

The software Statistica (StatSoft, Inc., 2300 East 14th Street, Tulsa, OK 74104, USA) was used to generate the experimental design and the results were subsequently analysed with multiple linear regression.

## Results and discussion

The flue gas concentration of carbon monoxide was used as the response variable in the initial study. Results for the 19 trials in the design are listed in table 3. The excess air did not vary substantially (O<sub>2</sub> ~17% vg).

*Table 3*  
*Measurement results (medians) for carbon monoxide (ppm sdg) in the initial study.*

Run	CO	Run	CO	Run	CO
1	228	8	2756	15	1387
2	264	9	3386	16	167
3	3408	10	1967	17	1328
4	2578	11	228	18	193
5	2629	12	1425	19	1352
6	228	13	1174		
7	1776	14	1308		

The span in measurement results for CO is a factor of 20. The recorded measurement results were therefore transformed to their natural logs prior to data analysis (also removing nonadditivity between factors).

Non-significant factors were removed after an initial regression analysis resulting in a final model of four factors plus a square-term for the temperature. The analysis of variance for this reduced response surface model is given in table 4.

*Table 4*  
*ANOVA for the reduced response surface model*

Source	SS	DF	MS	F	Prob.
Model	21.30	5	4.26	1484.93	<0.0001
B	0.32	1	0.32	111.30	<0.0001
C	16.90	1	16.90	5892.10	<0.0001
D	1.34	1	1.34	466.42	<0.0001
F	0.025	1	0.025	8.74	0.0111
C^2	0.97	1	0.97	336.40	<0.0001
Residual	0.037	13	2.87E-3		
Lack of fit	0.026	10	2.60E-3	0.69	0.7132
Pure error	0.011	3	3.77E-3		
Total	21.34	18			

Lack of fit is not significant indicating that the model adequately describes the recorded variations in CO. The model is unusually precise for a full-scale industrial experiment.

The coefficient estimates are given in table 5.

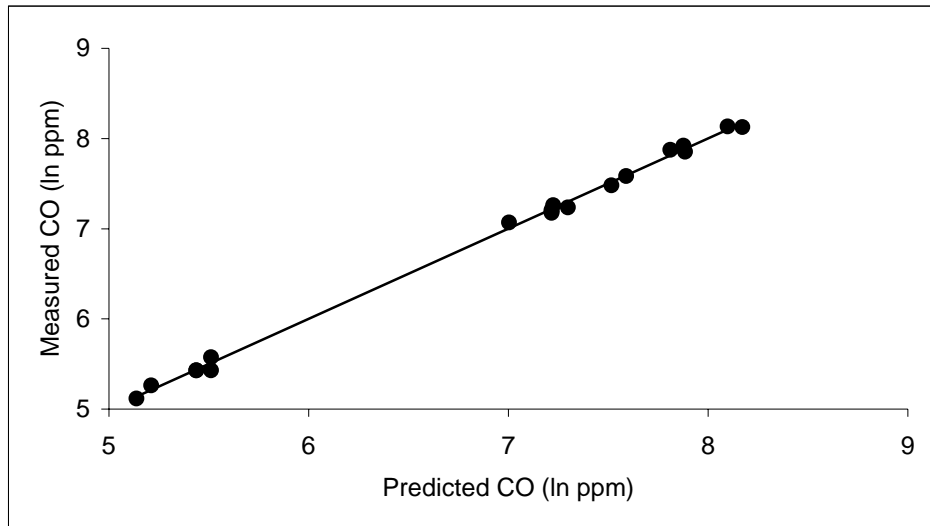
*Table 5*  
*Coefficient estimates, standard errors and 95% confidence intervals for the reduced response surface model*

Factor	Estimate	Std. error.	Low CI	High CI
Intercept	7.07	0.024	7.02	7.12
B: Line speed	0.14	0.014	0.11	0.17
C: Afterburner temp.	-1.19	0.015	-1.22	-1.15
D: Paint system	-0.29	0.014	-0.32	-0.26
F: Temp. Curve	0.037	0.013	0.010	0.064
C^2	-0.56	0.030	-0.62	-0.49

The final equation for the transformed response variable in terms of coded factors is:

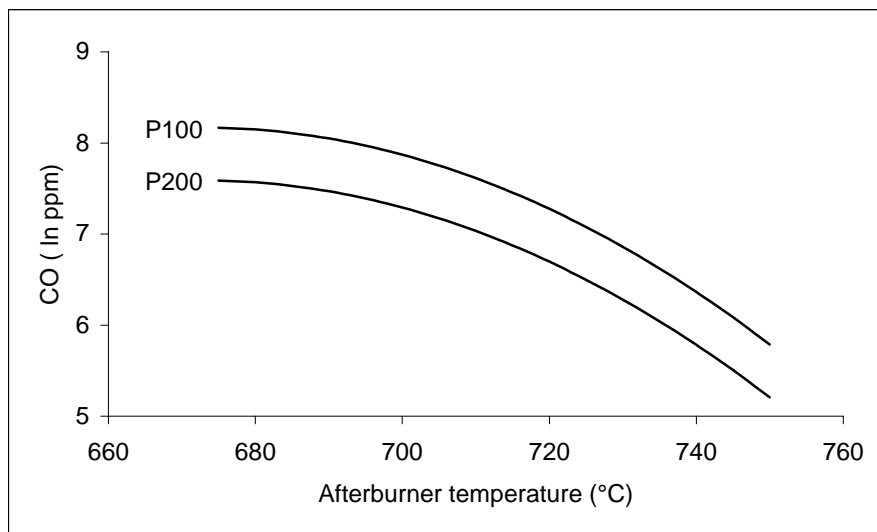
$$\ln(CO)=7.07+0.14*B-1.19*C-0.29*D+0.037*F-0.56*C^2$$

The measured versus predicted response (transformed scale) is shown in figure 1.



*Figure 1*  
*Measured vs. predicted response, CO (ln ppm, transformed scale).*

The most influential factor in this model is as expected the afterburner temperature, followed by the type of paint system. The estimated flue gas concentration of CO (transformed scale) versus temperature with each paint system is shown in figure 2, with the other variables at their normal set points (line speed 60 m/min and a reversed temperature curve).



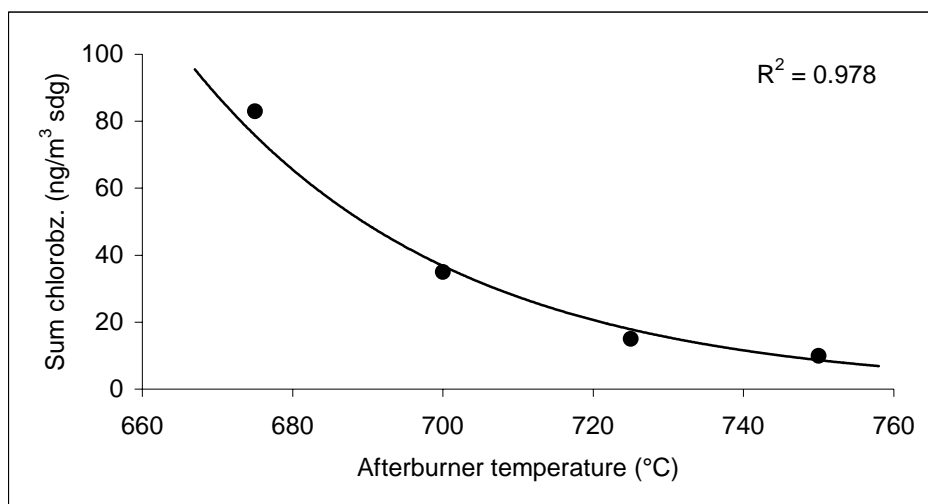
*Figure 2*  
*Estimated flue gas concentration of CO (ln ppm, transformed scale) vs. afterburner temperature (°C) with each paint system.*

It may at first glance seem surprising that the CO levels are higher with less coating thickness, but the paint system P100 is applied two-sided and consequently the evaporation of solvents is also higher. The increase in CO is obviously capacity related, and the temperature determines the destruction capacity in the afterburner chamber.

A basic hypothesis in this study was that the results obtained with carbon monoxide as response variable would also apply to other organic pollutants in the flue gas, e.g. chlorinated aromatics. A series of four verifying trials were completed five months after the initial study,

and this time flue gas samples were collected and analysed for chlorinated benzenes. Previous studies have clearly demonstrated that chlorinated benzenes are suitable as indicator parameters for other groups of combustion related chlorinated aromatics like polychlorinated dibenzo-p-dioxins and dibenzofurans [13-15].

Chlorinated benzenes showed a similar behaviour as carbon monoxide and an increased afterburner temperature reduced the already low concentrations further, figure 3.



*Figure 3*  
Concentration of chlorinated benzenes  $Cl_2$ - $Cl_6$  ( $ng/m^3$  sdg) vs. afterburner temperature ( $^{\circ}C$ )

A simple exponential model is fitted to the data in figure 3 and it indicates that a 50% reduction is achieved by increasing the temperature 25  $^{\circ}C$  anywhere within the investigated temperature range.

The measurement results for carbon monoxide agreed well with the model that was calculated from the initial trials, table 6. The afterburner combustion process is obviously very stable over this period of time.

*Table 6*  
Measurement results (medians) and model predictions for CO (ppm sdg).

Run	CO meas.	CO pred.
2:1	1500	1969
2:2	1360	1466
2:3	760	664
2:4	280	183

The decay of chlorinated benzenes with temperature was faster than could be expected from gas-phase thermal decomposition under oxygen rich conditions, based on calculations from experimentally derived rate constants [16]. This could indicate that flame decomposition is of more overall importance here, since it seem unlikely that we can find oxygen deficient conditions outside the flame periphery in this afterburner chamber.

Tsang (1987) has pointed out the importance of hydrogen atom induced decomposition for the thermal destruction of chlorinated benzenes [17]. Hydrogen atom attack on the chlorinated

aromatics will also affect the congener distribution as the rate constants for displacement increase with increasing degree of chlorination. Dellinger and Taylor (1998) report the same dechlorination of chlorinated aromatics due to displacement by hydrogen atoms [18]. If this reaction pathway were predominant, we would expect that the chlorination pattern should change and shift towards less chlorinated benzenes with an increase in temperature and destruction efficiency. The experimental data given in table 7 below seem to support this, and can be taken as a further indication that flame decomposition under oxygen deficient conditions is of major importance in the investigated afterburner chamber.

*Table 7  
Proportion and mass flow of dichlorinated benzenes  
at different afterburner temperatures.*

Temperature °C	675	700	725	750
Σ Dichlorobz. %	29.3	44.8	49.0	72.3
Σ Chlorobz. mg/h	2.0	0.82	0.35	0.23

The flue gas samples were also analysed for polychlorinated biphenyls (PCBs). The concentrations of PCBs in the stack varied between 0.2-0.3 ng/m<sup>3</sup>, and were not influenced by the combustion conditions. Previous passive in-situ monitoring indicate that the ambient air concentrations of PCBs are between 3-5 ng/m<sup>3</sup> in the surroundings. It can therefore not be ruled out that PCBs were present in the cooling air and that the measured flue gas concentrations is a sampling artefact.

## Conclusions

This experimental study in a full-scale industrial process is illustrative in several ways. First, it shows how one can adapt a design of experiment approach to the local process constraints and previously acquired experience regarding the importance of certain factors. Secondly, it demonstrates that a planned experiment can result in simple and understandable models with the same or even better precision that could be obtained from a laboratory experiment. Thirdly, it illustrates a step-by-step approach, where the most complicated and costly experiments are performed in a reduced second phase to verify the initial results. Last, it also shows how more fundamental knowledge from combustion theory and laboratory investigations can be used to further interpret and add to the purely empirical models.

The know-how obtained from this study will be used by the plant owner to further improve the process monitoring and control systems, and to continuously adapt the operating conditions to achieve a cost-effective and environmentally sustainable production process.

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