# Design of experiments and empirical models for up to date burners design for process industries

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## Abstract

At present period the application of complex models based on computational fluid dynamics (CFD) increases. At the same time, the cost of full experiments with high number of factors grows rapidly. In some cases, however, experimental approach cannot be fully substituted by computational modeling, which applies also to tuning of design of new burners. Due to high cost of experiments therefore grows the importance of properly designed experiments and statistical data analysis. Statistical experimental design and analysis is an indispensable tool for experimenters and one of the core topics in a statistics curriculum.

The present work deals with the design of experiment from its preparation, through experiment planning, that is followed by preliminary considerations about the model, implementation of the experiment and subsequent evaluation. Furthermore, we point out the problems of the performing of full experiment with high number of factors and outline the possibilities of creating the basis for fractional experiment. The experiment presented in this work is carried out at an up to date experimental facility for testing diffusion gas burners. The investigation focuses on the influence of design parameters on the formation of nitrogen oxides. Priority is however always given to the functionality of the burner (namely flame stability). This paper shows a convenient way how to set up the plan of expensive and time consuming experiments in testing industrial burners. Importance for industrial practice, equipment and consequently processes is demonstrated.

Keywords: design of experiments, statistical data analysis, empirical model, formation of nitrogen oxides

## 1. Introduction

Experiments are performed by investigators in virtually all fields of inquiry, usually to discover something about a particular process or system. A common goal in many types of experiments is to characterize the relationship between a response and a set of quantitative factors of interest of the researcher. This is accomplished by constructing a model that describes the response over the applicable ranges of the factors of interest. However, a little attention is paid to efficient carrying out of experiments during construction of the empirical models. Badly or insufficiently planned experiment can cause incorrect evaluation of acquired experimental data by employing any of statistical data analysis. Strictly speaking, it is necessary to set up such conditions in order to achieve the range of the experiment as small as possible and simultaneously high-quality information. This requirement is most important in experiments with high number of factors (independent variables). The design of experiment depends on particular solved problem, namely on the number of factors, the goal of experiment, the homogeneity or variability of experimental conditions. It is required to take into account the economical criteria, too. All the goals are fulfilled by properly designed experiments as well as by appropriate technical carrying out of experiments.

Experimental design is an important tool in the engineering world for improving the performance of process and it also has extensive application in the development of new processes resulting in e.g. improved process yields or reduced overall costs. Experimental design methods also play a major role in engineering design activities including for example evaluation and comparison of basic design configurations or determination of key product design parameters that impact product performance.

The development of efficient, low polluting combustion systems is a major goal of combustion researchers. Burner is always one of the key components of any combustion system. There are many factors related to the design of a burner that have significant impact on its emissions from its flame.

There are three predominant mechanisms for nitrogen oxides formation from combustion processes (Baukal, 2004):

- thermal $NO_x$,
- prompt $NO_x$,
- fuel $NO_x$,

where the thermal $NO_x$ formation is the dominating source in the combustion of natural gas. Nitric oxide is the primary $NO_x$ compound emitted from industrial combustion sources. It is even emitted if natural gas or hydrogen is used because it can be formed from air nitrogen and oxygen at high temperatures.

The dependence of $NO_x$ emissions concentration on various operating parameters is generally known. It was shown that the main factors which to a great extent influence $NO_x$ formation are the excess air and the temperature of preheated air (Carvalho et al., 1990, 1992). $NO_x$ increases with increasing combustion temperature and with increasing average furnace chamber temperature. Most $NO_x$ reducing techniques like staged combustion, gas re-circulation or water injection try to cut off peak temperatures, keep the residence time in high temperature areas low and avoid high oxygen concentration in these areas.

**2. Description of the testing facility**

Experimental data are presently obtained from testing a low-$NO_x$ burner in an up to date experimental facility intended for testing and improving industrial burners. The main apparatus of the burner experimental facility is horizontal water cooled combustion chamber with a maximum heat load approximately 1.8 MW (internal diameter of 1 meter, length of 4 meters). The cooling of the combustion chamber allows simulating conditions similar to conditions in the heating furnaces of the process industry. The cooling shell is split up to seven sections that gives the possibility to evaluate intensity of the heat flux along the flame. The next positive effect of the splitting in the sections is an improved water circulation in the cooling shell, thus avoiding local boiling caused by poor water circulation. There is one inspection hole (window) per each section that enables detailed observation of the flame and installation of measuring instrumentation.

The experimental facility is equipped with automatic data collection (temperatures, pressures, flows). The picture of the experimental facility is shown in Figure 1.

There was a possibility to measure concentrations of NO, $NO_2$, CO and $O_2$ by flue gas analyzer. Other measured data are as follows: flue gas temperature, temperature of combustion air, flow rate of combustion air and flow rate of fuel.

Experimental data is measured during testing of a gas burner with forced inflow of combustion air. Nominal duty of the gas burner was 0.93 MW. Gas injector stabilizing burner is used for flame stabilization.

Figure 1: Experimental facility.

## 3. Design of experiment

By statistical design of experiment, we refer to the process of planning the experiment so that appropriate data that can be analyzed by statistical methods would be collected, resulting in valid and objective conclusions. The presented design of experiment was employed with respect to the basic principles of experimental design, namely to replication, randomization, and blocking (Montgomery, 1991; Wu et al., 2000; Mason et al., 2003). The following chapters summarize the important steps that we had to address during the designing of experiment.

### *3.1. Objective of experiment*

The objective of the experiment is to investigate the influence of burner design parameters on the formation of nitrogen oxides and to find the relationship between the design parameters and the response.

The tested gas burner is of a diffusion-mixed type. Fuel staging was used, which means that secondary injectors in the burner are used to inject a portion of the fuel downstream of the root of the flame. Non-preheated atmospheric air is used as the oxidizer. Natural gas was used as a fuel.

### *3.2. Choice of factors and levels. Response variable.*

A review of the input factors (design parameters) which are varied in the experiment and the ranges of these factors may be found in Table 1. Limits of the factors were chosen to meet practical constraints. Response variable is the concentration of nitrogen oxides.

| Factors | Lower level | Upper level |
|---|---|---|
| Burner duty [kW] | 765 | 1120 |
| Diameter of swirl generator [mm] | 240 | 280 |
| Pitch angle of swirl generator blades [°] | 35 | 55 |
| Diameter of primary gas throttle [mm] | 5,5 | 6,5 |
| Air equivalence ratio [-] | 1,1 | 1,2 |
| Pitch angle of secondary nozzles [°] | 20 | 40 |
| Tangential orientation of secondary nozzles [°] | 0 | 45 |
| Radial position of secondary nozzles [mm] | 0 | 50 |
| Axial position of secondary nozzles [mm] | 0 | 80 |

Table 1: Burner design parameters.

Besides the response variable (nitrogen oxides concentration) are monitored also characteristic features of the flame like its diameter, length and shape, for each of the measurements. The character of these observations is however rather qualitative.

*3.3. Experimental plan*

In many industrial applications the response surface methodology is an effective tool to find the adequate model. Since the curvature effects are expected, the goal is to fit the second-order (quadratic) model in $k$ input factors

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon,$$

where $\beta_i$ represents the linear effect of $x_i$, $\beta_{ij}$ represents the bilinear interaction between $x_i$ and $x_j$, and $\beta_{ij}$ represents the quadratic effect of $x_i$, $\varepsilon$ is an error term.

An experimental design for fitting the second-order model must have at least three levels of each factor. The so-called central composite design is the most widely-used experimental design approach for fitting a second-order response surface. The design enables to construct the second-order model without needing to use the full three level factorial experiments. In order to carry out the full three level factorial experiment with high number of factors, extremely high number of test runs would be required, approximately 20000. This would be very time consuming and costly. Due to limitations given by nature of the present experiment, the central composite design was selected, which requires far less measurements than in a $3^k$ factorial experiment design.

The actual design employed in the experiment is a special form of the central composite design in that the axial points are located on the centers of the faces. Thus, the design is called a face-centered central composite design and uses only three levels of each factor. The design consists of the following three parts:

1) $2^{k-2}$ fractional factorial layout, where $k = 9$ is the number of the input factors. Thus the number of cube points was $n_f = 2^{9-2} = 128$.
2) $2k$ axial points along the coordinate axis. Each pair of axial points is denoted, using coded levels, as follows:

$$\begin{gathered}(\pm\alpha, 0, 0, \cdots, 0),\\ (0, \pm\alpha, 0, \cdots, 0),\\ \cdots\\ (0, 0, 0, \cdots, \pm\alpha),\end{gathered}$$

   where $\alpha = 1$ for the face-centered central composite design.
3) $n_c = 1$ center points $(0, 0, \ldots, 0)$.

The number of test runs in the plan is equal to $N = 2^{k-2} + 2k + n_c = 147$ without replication. In order to be able to estimate the experimental error and to increase the reliability of conclusion, the basic experiment was replicated three times. Thus, the total number of test runs in the experiment is 441.

Since in general most new settings of factor levels for individual test runs would require shutdown and dismounting of the burner, the order of test runs in the experiment is not completely random. The order of test runs was arranged in such a way that the setting of each test run requires the smallest possible number of changes of factor levels (compared to the respective preceding run). The benefit of resulting time-savings in the factor-setting stages is that the temperature of the combustion chamber walls does not decrease too much between individual test runs. Thus further time and fuel savings result, as equilibrium conditions for new measurement are attained quickly.

The technique of blocking is not applied to the plan of experiment even though the temperature of combustion air fluctuates during the whole experiment (depending on ambient conditions in the laboratory). The variation of temperature of combustion air is about ±10°C around the mean value. This however has a negligible influence on the measured response.

## 4. Preliminary results

At the moment of completing this text, only a part of measurements is completed. Expected time interval of test runs, necessary to reach steady temperature of the combustion chamber walls in each of them has been confirmed and is approximately 20 minutes. This period is minimized by suitable ordering of test runs as described above.

The preliminary results reveal that the concentration of $NO_x$ emissions has decreased with increasing radial position of secondary nozzles as well as with increasing clockwise tangential orientation of secondary nozzles (reference orientation is that the secondary nozzles are oriented to the burner axis). Next, the concentration of nitrogen oxides has increased with increasing pitch angle of secondary nozzles. The change of axial position of secondary nozzles has shown a small influence on the change of $NO_x$ concentration.

## 5. Conclusion

The present work presents the proper way to create a smallest sufficient plan of experiment while respecting statistical requirements of the theory of experiment design. The principles of experiment design were implemented during the construction of a plan of measurements for testing a low-$NO_x$ gas burner. Face-centered composite design of experiment was proposed that is sufficient for this kind of experiment in spite of small number of test runs.

The presented design that was proposed is specific for the given type of burner. However, the methodology of proper experiment design can be applied to various types of burners.

## 6. Future work

Future work will consist of carrying out the measurements according to the designed plan of experiment. This will be followed by construction of the empirical model by employing statistical data analysis. The aim of the model is further improvement of the predictive capabilities of $NO_x$ in the field of burner design.

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