Abstract:

Computing, make complex designing of industrial equipment, like furnaces, possible. The goal of furnace companies: designing and building the best furnace for a given technology, and having a safe, optimized price, capacity and gas emission rate before selling the product. This needs designers, with a new way of thinking. Paper offers a complete method and software for this type of business activity.

In Europe most of industrial furnaces are fired with natural gas... Natural gas firing has relatively low NOx, CO and CO$_2$ emission and in the last decade new technologies where made for decreasing it. At control emission of hazardous materials, methods where found keeping it at a low level: like the forced flue-gas recirculation, more step combustion, even water injection and increasing of air factor, (at low temperature heat treating furnaces). Keeping hazardous emission low is very important. At low flame temperature maximum, NOx emission decreases and CO emission increases. This is one of the reasons, which makes building furnaces (and burners) with “very slow mixing” so difficult. Research was made at the University of Miskolc (Hungary), for calculating the parallel NOx and CO emissions. A program, which collect all the influencing factors, (the physical chemical and mass and heat transfer), of NOx and CO emission in common system makes “what if...” calculations possible. Research was financed by OTKA T-46530 project. Furnace calculation, size, walling, burners, firing and protective gas system are based on the well known combustion, and heat- and mass transfer rules.

Key words: furnaces, natural gas firing, efficiency, emission, sale.

1.0 The “complex design” theory.

Complex design means: to be able to give an offer to the customer within 4 hours, after receiving the tender. Complex design is based on computer programs, which are able to cooperate, and to take all the important data into consideration.

- A “Sales” program, which is ready to print a complete offer with optimal technical and technological part, and which contains the best price, technology and guaranty conditions.
- A “Furnace” program, which can design a new furnace, to meet the optimum for the tender.
- A “Nox” program, for computing combustion, mass and heat transfer, charge-time, efficiency and emissions.

1.1 Sales program.

Furnace companies have their own profile, and list of reference and prices. This data-bank contains information, (size, weight, number and price in previous cases, charge time, capacity per m$^2$, etc.) In some cases, seller tries to sell a standard furnace from his list for similar works, but the offer will be week, capacity: size, mass, quality of product and price will not meet the optimum. The seller not having a quick control possibility do not know the losses in capacity, quality and price, made by offering an old design, and looses the business because of a week offer. This program shows differences between offering an “old” furnace and an up to date one. Sales manager need make own decisions only on price and delivery time.

1.2 Furnace program.

After input the tender data, this program compute the heat balance, heating data, fuel consumption, different losses, air demand, and flue volume and temperature of a furnace, designed for the tender conditions. Gives optimal sizes, walls, heat exchangers, mass of load and specific energy consumption, because makes “what if...” calculations possible. [4].
1.3 Nox program.
NOx program imports furnace-data from “Furnace program”, and calculate influence of specific technological positions, like type of burners, load quality, size and temperature, enthalpy of fuel and air, position of load- and hearth temperature. Computes gas emissions, important at environmental protection and sales position.
In the following we show in, how the 1.2 and 1.3 programs, made at the Chair of Combustion Technology of University Miskolc, Hungary, are working, [1, 2, 3, 4, 5, 6, 7].

2. Computing of heat balance and Nox-CO emission of industrial furnaces
The metal reheating and heat treating furnaces of steel industry, are big users of fossil energy. In the last 50 years natural gas became the most important fuel in Europe. Natural gas is a clean, easily adjustable and transportable fuel, which has relatively less carbon content than coal and oil, and therefore less NOx, CO and CO2 emission.

When accepting the NOx as the most dangerous emission at natural gas firing, a high temperature (800-1400 ºC), furnaces producing more emission at similar capacity, than the low used in rolling mills, temperature ones. That is why we are going to analyze the emission of soaking pits, walking beam- and tunnel type furnaces.
At calculating the NOx+CO emission, a lot of factors which are influencing the flame temperature, should be taken into consideration:

2.1 Calorific value and physical properties of gases:
1./ Components of fuel, natural gas: %.  
2./ Air factor of combustion,  
3./ Theoretical volume of oxygen, m3/m3.  
4./ Theoretical volume of air, m3/m3.  
5./ Volume of air, m3/m3.  
6/ Volume of flue gas components, m3.  
7./ Heat capacity of fuel, kJ/m3.C.  
8./ Heat capacity of flue gas, kJ/m3.C.  
9/ Heat capacity of air, kJ/m3.C.  
10./ Temperature of gas, ºC.  
11./ Temperature of Air, ºC.  
12./ Theoretical Flame temperature, ºC.  
13./ Pyrometric efficiency, 1  

2.2 Influence of burners and furnace hearth:
14./ Shape of furnace hearth:  
15./ Bottom length, and width : m.  
17./ Height of hearth: m.  
18./ Specific heat input: kJ/m³.h.  
19./ Swirl-number of burners: 1.  
20./ Spec. impulse-force of burners: N/kW.  

2.3 Influence of load and load placing:
21./ Mass of load, kg.  
22./ Cold temperature of load: ºC.  
23./ Hot temperature of load, ºC.  
24./ Time-temperature curve, ºC/h.  
25./ Heat capacity of load, kJ/kg.C.  
26./ Furnace time, h.  
27./ Size of load, (L,W,H): m.  
28./ Number of charge: 1.  

3.0 Data and results from the tender.
Data of existing equipment and technology are to find in questioner, filled in by the buyer (shop or the company). For computing the heat balance:

1. Capacity, (output, t/h, components of heating gas, metal quality and temperature).  
2. Data of furnace hall, (type, height of cranes, capacity, type of loading, size of doors, etc.).  
3. Load: (material, type: blocks, pipes, plate, wire coils, mass, size and number of pieces, location, type of loading, surface of heat exchange.)  
4. Technology: (melting, reheating, heat treating, or drying, heating up curve and soaking time, heat input in furnace time, charging-temperature, temperature-time diagram, end-temperature of charge.)  
5. Other data, influencing the flame temperature maximum: (Hearth temperature at loading, water cooling, openings on walls, etc.)

4. FURNACE program
This program can be used for computing data of a new furnace. We suggest the following steps:
1./ From data of charge and furnace capacity calculate the measures of the bottom, and the height of the hearth, fix the placing of doors and burners..  
2./ Select the refractory materials and the insulation for the walls, bottom and roof.  
3./ Make a simple drawing of furnace hearth in horizontal and vertical sections.  
4./ Fix the air preheating conditions.  
5./ Chose firing system and burners, (energy input, capacity and type of burners., mixing type, (swirl or parallel), specific impulse-force (air velocity x mass of fuel/kW, swirl number).  
6./ Fix the heat consumption of auxiliary equipment, (water cooling, bottom cars, loading tools), the timetable of furnace, (continuous, in one shift/day) and the heat generating, (scaling, out-burning) heats.  
7./ Put in data into the page of the FURNACE program.
4.0 Data from cold and hot modeling, literature and FLUENT calculations.
1. Flow system and velocities of flue gas in circle and square hearths.
2. Influence of burners placing on convective heat transfer
3. Influence of size and form of load on flame temperature.
4. Influence of placing of load on radiating heat transfer.
5. Influence of burner on flow velocity, heat transfer and recirculation efficiency.
6. Equation for calculating NOx emission between 900-1300 °C hearth temperature.
7. Equations for computing NOx emission at forced flue gas injection into the combustion air.
8. Equations for computing NOx at spraying different mass of water into the combustion air.
9. Equations for computing NOx emission at different air number, (0-1,4)
10. Equations for computing NOx at two step air, and two step gas introducing.
11. NOx emission at very slow mixing of gas and air. (“Burning with no flame”).
12. Changing NOx emission at different impulse-force.
13. Equations for calculating CO emission at different furnace temperature and mixing.

There where not complex methods for calculating the work and NO emission of furnaces. In the last fifteen years continuous and systematic research was made at the Chair for Combustion Technology of University Miskolc with the financial help of Hungarian Research Foundation (OTKA) to find relationship among the firing and heat transfer, energy efficiency and the NOx and CO formation.

In two research furnaces, (1990-1995, 1995-2005), insulated with ceramic fibers walls and equipped with moving water cooling probes for the temperature regulation of the hearth, thousands of measurement were made of NOx and CO emission at different hearth- and flame temperatures, and air factors. Influence of forced input of CO2 in air, the two step air injection, in the air injected water, and the influence those on the emitted values where measured, [1,2,3]. All this experiments was made in the same furnace, with the same instruments and temperature and pressure conditions. Most of the calculations are based on research made in half-industrial size equipment and with industrial instruments. The results may contain a ± 5% mistake.

5.0 Program for designing furnaces and overall analyzing of NOx+CO emission.

The NOx research work was limited for chamber type furnaces and furnaces, where load is on the furnace bottom and flame is over the load. Calculation of NOx+CO emission where made in two independent programs: FURNACE program and EMISSION program. The programs work in a "FRAME", (Page 1.) which coordinate the data and results. Starting with the FRAME, calculation starts with clicking on the upper button, "Heat balance and gas consumption" (in the followings “FURNACE”), and filling in data in the left side of page. An EXCEL program, “heatblnc.xls”, compute the details of heat input and output of furnace, and prints the heat balance in the right upper part of the page.

![Fig 1. The “FRAME”](image)

There are four “secondary” excel programs behinds the main program, parts of “heatblnc.xls” excel file. By clicking on one of the buttons in the left lower part of the page these programs operate:
From program 1/a, (page 3.), after input of gas components and temperature of air and gas come the air demand, volume of flue gas, and calorific value of gas. (The FURNACE program can be used at oil firing, NOx program is made for gas firing, only). By clicking on “calculation” button, data will be transferred to the main program.

From program 1/b, (page 4), after input of surfaces, thickness and heat conducting and transfer data, heat losses of flat surfaces: side, roof, bottom and end wall will be printed.
From program 1/c, (page 5). Will be transferred the heat losses of the corners and edges.

With program 1/d are transferred important data of the designed or existing furnace, like: gas and air volume in time, gas and air temperature, data of heat exchanger, furnace efficiency, flue gas volume and temperature at different places, etc. At the lower part of the page are buttons for saving the program or importing another one we worked with earlier, changing the languages Hungarian/English, and “Quit.”

Clicking on the “Quit” button we return to the “FRAME”. All the results are transmitted to the “EMISSION” page. For calculating the burner, the heat transfer and flame temperature in the hearth and for checking the NO (NOx) and CO emission we click the “Calculation of heating up and flue-gas emission” button, (In the following “EMISSION”).

7.0 Calculation the chemical and physical data of gas and flue gas.

The first step is: filling in the components of fuel, air number, volume and temperatures into the left side of page. Program calculates volume of combustion air at the real value, by writing the usual gas volume in the window on the top of the page. After finishing the input, program calculate the heat balance of the furnace and print it in the right side of the page.

For details of combustion click the “Combustion calculations” button for volume of the air and flue gas, components and the heat capacity of the flue gas and its components. If furnace has an air and/or gas heater, the temperature of gas and air must be written in Fig.4.

On left lower corner of third page is the calorific value of fuel gas to find. Kicking on “Quit” we return to Fig 3.

For completing of heat balance wall losses must be calculated. It will be made by the Fig. 5 and 6. In Fig 5. We input wall data of plain surfaces, (size, thickness, heat conductivity, outside- and inside temperatures, emission and heat transfer coefficient of heat transfer by convection):

Heat losses of corners and edges will be calculated similar way on Page 5.
FURNACE program is computing all the important data of gas and air consumption, temperatures, and furnace efficiency. These are printed in Fig 7 and can be read with clicking on “Computed results”, button on Page 2.

**COMPUTED RESULTS.**

<table>
<thead>
<tr>
<th>Escaped burning produced,</th>
<th>Flue gas temp.</th>
<th>Flue channel losses,</th>
<th>Specific energy consumption, kJ/kg, 1263</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel needed, piece/h</td>
<td>204</td>
<td>Th. flame temp., °C</td>
<td>2168</td>
</tr>
<tr>
<td>Air consumed, m3/h</td>
<td>1996</td>
<td>Ac. flame temp., °C</td>
<td>1300</td>
</tr>
<tr>
<td>Flue gas produced, m3/h</td>
<td>2085</td>
<td>Iron/air Chamber, °C</td>
<td>850</td>
</tr>
<tr>
<td>Basic design block,</td>
<td></td>
<td>Before recuperator, °C</td>
<td>850</td>
</tr>
<tr>
<td>Total burn gas, m3/charge</td>
<td>10423</td>
<td>Flue after recuperator, °C</td>
<td>589</td>
</tr>
<tr>
<td>Total fuel gas, m3/charge</td>
<td>1013</td>
<td>Air after recuperator, °C</td>
<td>621</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total burn gas, m3/h</td>
<td>2085</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fuel gas, m3/h</td>
<td>204</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel losses, kJ/charge</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recuperator losses, kJ/charge</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific energy consumption, kJ/kg</td>
<td>1263</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Economical data.**

<table>
<thead>
<tr>
<th>Gas consumption, m3/h</th>
<th>203.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency, %</td>
<td>67.64</td>
</tr>
<tr>
<td>Specific energy cons., kJ/m3</td>
<td>1263</td>
</tr>
</tbody>
</table>

**Heating up at cold start, kJ/charge.**

<table>
<thead>
<tr>
<th>Mass of wall, kg</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water equivalent, kJ/kg, K</td>
<td>0.35</td>
</tr>
<tr>
<td>Wall temp, changing, K</td>
<td>800</td>
</tr>
</tbody>
</table>

**For tools.**

<table>
<thead>
<tr>
<th>40.0000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of car, kg</td>
</tr>
<tr>
<td>Number of car, db/h</td>
</tr>
<tr>
<td>Temp of car, °C</td>
</tr>
<tr>
<td>Heat capacity, kJ/kg, C</td>
</tr>
</tbody>
</table>

With a click we return to Page 3. Here we can finish the computing. By clicking on the “Save as…” button, makes saving of all pages and data of furnace possible. With a quit on 2. Page we return to FRAME.

8.0. Computing of charge temperatures and NOx-CO emission.

**Fig 6. Sixth program Page.**

**Fig 7. Seventh Page of program.**
After computing the furnace data by using the upper button of frame, clicking on the lower button we can calculate the temperature of charge and the gaseous emissions.

The “Step 1” calculate the heat transfer by flame radiation and the flame temperature in hearth, the data of combustion, base data of the firing, pyrometric efficiency. The real flame temperature is lower than theoretical, printed on the left side of Page 7. The difference can be detected by the input of “pyrometric efficiency”. This factor depends on the intensity of heat transfer from the flame. At high flame radiation, flame temperature-maximum decreases. The emission factors of radiation where calculated with the Shack method.

Better mixing of gas and air makes pyrometric efficiency better. Mixing velocity can be distinctive by the “Swirl number” and “Specific impulse force” of burner, (burners). Button on the lower right side of page makes changing language possible.

1. step: Flame radiation and temperatures.
2. step: Influence of the firing system,
3. step: Influence of heating technology,
4. step: NO-NOx emission,
5. step: Decreasing the NOx emission by classic methods.
6. step: Furnace and flame temperature in the first part of charge time,
7. step: CO emission. Calculating the specific mass of NOx+CO emission at different circumstances.

A button behind “Pyrometrical efficiency” opens the page 8, “Flame radiation”.}

![Fig. 8. Eighth page of the program](image)

This matrix estimates the flame temperature at different distances from the burner. The flame length is divided into 5 sectors of length. Matrix estimates the temperatures with iterative way. (Enthalpy of mixture plus burning heat in the first sector, minus the flame radiation from that sector gives temperature maximum of flame, there. After finishing with the first, goes to the second sector.

Having the temperatures in all sectors, program uses the maximal temperature of flame for estimating the NOx emission of furnace.) Summa of flame radiation in all sectors, makes estimating the heat transfer to charge possible. The matrix help to find optimum in heat transfer and flame temperature at “what if ?” type analysis.
Fig 9. Last page, of EMISSION program, the “Second step”.

By clicking on the “« Step 1” button, we return to “First step” page. (Results are transferred from the page into the main program.)

Swirl Nr. and velocity of fuel and air influencing the mixing and burning conditions. From the “Step 1” page we can go to the “Step 2.” page, which one contains practical data of furnace: Cross sections of hearth, size and location of load, material and heat capacity of charge, and the heating up time and temperatures of load in time periods. Most of the data come from the “Furnace” calculations.

Emission of NO (NOx) is printed in the lower-left corner of the page. The base emission can be corrugated in case of mixing H2O, CO2 into the flame, or working with two step air or gas injection. The results of these technologies are printed below the base emission data, and are summed up in the last line.

With the “Save as...” button the data and results will be transmitted in a default file. The default files of different types of furnaces are ready for opening and reuse in any time.

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9. References: