STUDY OF EMISSIONS FROM A COOKING RANGE

M. MOYA and J. D. RIVERA*

Departamento de Ingeniería Mecánica,
Pontificia Universidad Católica de Chile, Santiago, Chile

We study the effects of two design parameters on emission indices of a cooking range. The parameters are the distance between the burner head and the bottom of the pot, and the primary air ratio. We measured the NO and CO emissions and thermal efficiency of two burners of different heating capacity. The same batch of commercial propane was used in all the tests. Results show that increasing pot-to-burner distance decreases CO emissions and efficiency and increases NO emissions. The effect of reducing primary air is to increase CO and efficiency, and to decrease NO.

Keywords: Cooking range; Premixed combustion; Propane emissions; Domestic gas burners; Emission optimization

INTRODUCTION

In the last several years there has been a growing concern about indoor air quality. EPA (1995) points out that there is evidence that the air inside homes and other buildings can be more seriously polluted than the outdoor air in large cities. In most houses there is more than one source of pollution. Some of them include tobacco smoke, biological contaminants, household products, and combustion products from unvented domestic appliances, such as some space heaters and gas cooking ranges. Each source independently produces a cumulative effect into the total air pollution. The exposure to those sources can bring a variety of health risks, especially in people that spend a long time indoors, like babies, the elderly, and sick people.

Some of the more typical and dangerous indoor pollutants are CO and NO₂. They are generated mainly from burning fuels in unvented domestic appliances, and their health risks can range from headaches and irritations to death in the most critical cases.

In the last few years the problem has attracted the attention of researchers and several works have been published. However, most studies are focused on space heaters, like Yamanaka et al. (1979), Traynor et al. (1983), Tu and Hinchliffe (1983), Apte and Traynor (1986), and Traynor et al. (1990), who studied emission rates for gas and kerosene space heaters.

*Address all correspondence to Dr. Juan de Dios Rivera, jrivera@ing.puc.cl.
Given the limited number of studies about pollution produced by cooking ranges, this study was devised to contribute to the knowledge in this area, helping to assess the source of indoor air pollution. CO and NO emissions were analyzed in a domestic propane-fueled cooking range for two different design parameters: the distance between the top of the burner and the bottom of a common cooking pot, and the primary air ratio. Two different but similar burners were used, both pertaining to the same cooker but with different heating rates.

EXPERIMENTAL DETAILS

Tests were conducted in a Fenza 1000 cooking range, built to burn fuel gases of the third family, according to the European Norm EN 30 (1979). This type of range, typical in Chilean households, has two burners and an oven. The range was implemented with an adjustable grill, which permitted the regulation of the distance between the bottom of the pots and the top of the burners. Because of simplicity, the distance between the lower part of the grill and the top of the burner was measured and recorded. Tests were performed with grill-to-burner distances ranging from 0 to 25 mm, increasing in 5-mm steps. To obtain the pot-to-burner distance, it is necessary to add the grill thickness, 6 mm, to the grill-to-burner distance.

The fuel used in the tests was commercial propane, with a chromatographic analysis as shown in Table I. Other fuel properties, calculated from the chromatographic analysis according to ASTM D 3588-91 (1991), are shown in Table II.

<table>
<thead>
<tr>
<th>Hydrocarbon</th>
<th>Formula</th>
<th>% vol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td>97.67</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>0.73</td>
</tr>
<tr>
<td>Iso-Butane</td>
<td>C₄H₁₀</td>
<td>1.06</td>
</tr>
<tr>
<td>Butane</td>
<td>C₄H₁₀</td>
<td>0.51</td>
</tr>
<tr>
<td>Iso-Butene</td>
<td>C₄H₈</td>
<td>0.01</td>
</tr>
<tr>
<td>Cis-2-butene</td>
<td>C₅H₁₀</td>
<td>0.01</td>
</tr>
<tr>
<td>Iso-Pentane</td>
<td>C₅H₁₂</td>
<td>0.01</td>
</tr>
</tbody>
</table>

| Density, ρ   | 1.9 kg/m³ |
| Higher heating value, HHV | 51.25 MJ/kg |
| Lower heating value, LHV  | 47.15 MJ/kg |
| Molecular weight, MW      | 44.22 kg/mole |
| Compressibility factor, Z  | -0.9825 |
Propane pressure was regulated to 2.75 kPa (280.5 mm WG), following EN 30 (1979), and measured with a water gauge. This pressure was held constant for all tests.

**Burners**

The burners are of the laminar, partially premixed type, operating on the Bunsen-burner principle. The fuel jet exiting the gas nozzle entrains air, and the mixture is burned in a group of port openings evenly distributed in the circumference of the burner-top disc. The two burners, which have an actual heat release rate of 2.3 kW and 1.6 kW, were designated A and B, respectively.

The primary air ratio was one of the parameters that was changed. For this purpose, a special mechanism that restricts the primary air entrance was made. It consists of a sleeve that slides onto the mixing tube in such a way that it can decrease the distance between the fuel nozzle and the entrance to the mixing tube, with the consequent decrease in the amount of air entrained. Tests have shown that over an appreciable range of distances, where the orifice is neither too close nor too far away, the air entrainment remains constant (Lewis and von Wlbe, 1961). This reason forced us to slide the sleeve very close to the fuel nozzle, leaving a very small distance between the orifice and the mixing tube entrance, in order to achieve a noticeable change in the primary air ratio. Emissions and thermal efficiencies were obtained for each burner, working with either unrestricted or restricted air entrance.

**Fuel Gas Nozzle Coefficients**

Neglecting compressible flow effects and fuel gas velocity inside the pipe, gas flow exiting the nozzle, \( m_f \), is expressed as

\[
m_f = K_N \sqrt{2 \rho (p_1 - p_2)} A ,
\]

where \( K_N \) is the nozzle flow coefficient, \( p_1 \) is the gas supply pressure, \( p_2 \) is the ambient pressure, \( \rho \) is the gas density, and \( A \) is the nozzle cross-sectional area. Actual fuel gas flow was measured for each burner by weighing the propane cylinder with a high-precision scale, and the nozzle flow coefficient was calculated:

\[
K_N = \frac{m_f}{A \sqrt{2 \rho (p_1 - p_2)}}
\]

**Thermal Efficiency**

Thermal efficiency can be defined as the ratio between the effective energy used for heating the pot and the total energy in the fuel consumed. It was measured
and calculated following the European Norm EN30 (1979), where more details can be found. The heat release rate for each burner was calculated from the gas flow rate:

\[ \dot{Q} = m_fHHV \]  

(3)

The size of the pot to be used for measuring the efficiency, according to EN30 (1979), is calculated as follows:

\[ S = \frac{\pi D^2}{4} = 191\dot{Q} \]  

(4)

where \( S \) is the pot-bottom surface area (in cm\(^2\)), \( D \) is its diameter (in cm), and \( \dot{Q} \) is the heat release rate (in kW). Once obtained, the pot diameters for each burner [EN30 (1979)] indicates the mass of water, \( m_w \), that has to be heated in the pot from 20\(^\circ\)C ± 1\(^\circ\)C to 90\(^\circ\)C for measuring the efficiency. Finally, thermal efficiency is calculated as

\[ \eta = \frac{m_wC_p(T_2 - T_1)}{m_fHHV} \times 100 \]  

(5)

where \( m_w \) is the mass of water in the pot, \( T_1 \) and \( T_2 \) are the initial and final water temperatures, respectively, and \( m_f \) is the mass of fuel consumed in the test.

**Emissions Indices**

A flue-gas sample to be analyzed for pollutants was obtained using a hood that covers the pot, with a separated discharge of the combustion gases and the vapor generated by the hot water. This hood corresponds to a special combustion essay appliance and was put on a 22-cm-diameter pot with 3.7 kg of water, as described by EN 30 (1979). The probe of a TESTO 300 gas analyzer (which measures CO, NO, and O\(_2\), simultaneously) collected a sample of the combustion gases. The analyzer was connected to and controlled by a microcomputer, where data was stored every 3 s for further processing. NO\(_2\) was measured with a TESTO 350 gas analyzer for a few tests, to determine the NO\(_2\)/NO ratio. This second gas analyzer was not used in all the tests because of availability and because it could not be connected to a microcomputer.

Emission indices based on the fuel mass, expressed as grams of pollutant per kilograms of fuel, were calculated as described by Turns (1996):

\[ EI_m = \frac{\frac{1000X_iMW_iC}{(X_{CO_2} + X_{CO})MW_f}}{ } \]  

(6)

where the subindex \( i \) stands for the pollutant, and \( C_{CO_2} \) was calculated as
\[ X_{\text{CO}_2} = \frac{X_{\text{CO}_2}(21 - X_{\text{O}_2})}{21} - X_{\text{CO}} \]  

(7)

where \( X_{\text{CO}_2} \) corresponds to the \( \text{CO}_2 \) molar fraction, resulting from an ideal stoichiometric combustion process for the actual fuel gas. According to the chromatographic composition of the fuel gas, the calculated value for this parameter is 13.765. The emission indices as calculated in this research are valid only for the process of heating water to a temperature close to its boiling point because this is the process specified for the efficiency measurement, according to EN 30 (1979).

Since what really matters is the heat used in heating the pot content, an emission index based on the energy consumed was defined first and, later, a corrected emission index (CEI) was defined that takes into consideration the efficiency in heating the water:

\[ EI = \frac{E_{m}}{\text{HHV}} \]  

(8)

\[ \text{CEI} = \frac{E_{m}}{\text{HHV}\eta} \]  

(9)

The corrected emission index is used to assess the real effect of the studied parameters, pot-to-burner distance, and primary air ratio on indoor air pollution. The units of the CEI are grams of pollutant per MJ of actual heat delivered to the water. Emissions of \( \text{CO}, \text{NO}, \) and \( \text{NO}_2 \), and thermal efficiency were measured for both burners, each one working with two different air ratios and six pot-to-burner distances.

RESULTS AND DISCUSSION

Nozzle Flow Coefficient

We measured the actual fuel gas flow by weighing the propane cylinder, which allowed us to calculate the nozzle flow coefficient for each burner. This permits to estimate the gas flow for different pressures and gases, without the need to weigh the gas cylinder, which can be cumbersome for large-size cylinders. Table III shows the nozzle cross-sectional area, the fuel-mass flow measured in the scale, and the calculated flow coefficient.

Thermal Efficiency

The thermal efficiency for burners A and B, both working under unrestricted and restricted primary air entrance, were measured and calculated following the method described above. Ideal pot diameters obtained following EN 30 (1979)
were approximated to the nearest integer. Table IV shows thermal consumption (or heat release rate), pot section and diameter, and water mass used, according to EN 30.

Table V shows the thermal efficiencies obtained for the burners working both under unrestricted and restricted primary air conditions. For all cases, results show that thermal efficiency increases as the pot-to-burner distance is reduced. There are two facts that explain this result. The first one is that high-temperature combustion products from the flame mix with cold ambient air, which results in a reduction of the mixture temperature in relation to the combustion products. As the distance between the pot and the burner gets larger, the combustion products have the opportunity to mix with more cold air before impinging on the pot-bottom surface with a further decrease in temperature. Hence, the hot gases seeping by the pot take more heat, and less heat is transferred to the water. This phenomenon increases the time the water takes to reach its final temperature and, therefore, increases the fuel consumption of the test. Thus, the thermal efficiency decreases. The second explanation is that with increasing pot-to-burner distance, more heat is radiated to the surroundings from the hot combustion products and the burner top. Probably this second effect is not as important as the first one.

---

**TABLE III** Nozzle flow coefficient

<table>
<thead>
<tr>
<th>Burner</th>
<th>(A, \text{ m}^2)</th>
<th>(m_f, \text{ kg/s})</th>
<th>(K_N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.81E-7</td>
<td>4.52E-5</td>
<td>0.76</td>
</tr>
<tr>
<td>B</td>
<td>3.89E-7</td>
<td>3.16E-5</td>
<td>0.79</td>
</tr>
</tbody>
</table>

**TABLE IV** Thermal consumption, pot recommended section and diameter, actual pot diameter, and water mass used for each burner

<table>
<thead>
<tr>
<th>Burner</th>
<th>(T_c, \text{ kW})</th>
<th>(S, \text{ cm}^2)</th>
<th>(D_{\text{recomm}}, \text{ cm})</th>
<th>(D_{\text{used}}, \text{ cm})</th>
<th>(m_w, \text{ kg})</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.274</td>
<td>434.3</td>
<td>23.5</td>
<td>24</td>
<td>4.8</td>
</tr>
<tr>
<td>B</td>
<td>1.590</td>
<td>304.0</td>
<td>19.7</td>
<td>20</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**TABLE V** Average thermal efficiencies for burners A and B, working under both unrestricted and restricted primary air conditions

<table>
<thead>
<tr>
<th>Grill-to-burner distance, mm</th>
<th>Burner A (2.274 kW)</th>
<th>Burner B (1.590 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unrestricted, %</td>
<td>Restricted, %</td>
</tr>
<tr>
<td>0</td>
<td>54.2</td>
<td>54.6</td>
</tr>
<tr>
<td>5</td>
<td>53.1</td>
<td>54.2</td>
</tr>
<tr>
<td>10</td>
<td>50.8</td>
<td>53.3</td>
</tr>
<tr>
<td>15</td>
<td>47.2</td>
<td>50.9</td>
</tr>
<tr>
<td>20</td>
<td>44.4</td>
<td>50.2</td>
</tr>
<tr>
<td>25</td>
<td>42.2</td>
<td>48.1</td>
</tr>
</tbody>
</table>
Figures 1 and 2 show a comparative graph of thermal efficiency versus grill-to-burner distance for each burner, working with unrestricted and restricted primary air. The graphs show that thermal efficiency increases when the grill gets near the burner, for both primary air conditions. The graphs also show that when the pot is close to the burner, there is a small difference between the restricted and unrestricted air cases, and when the distance grows, there is a steeper decrease in the efficiency for the unrestricted case.

It is worth noting that efficiency is always larger for the restricted case, with the exemption of burner B at the smallest grill-to-burner distance. In this situ-
ation, flame quenching by the cool bottom of the pot is significant, producing a large-enough amount of unburned products to affect thermal efficiency. This is corroborated by the fact that CO emission in this condition is larger than in any other and presents the largest difference with the unrestricted air case for the same burner- and grill-to-burner distance, as can be seen in Figure 4. Also, flame impingement in the bottom of the pot under these circumstances was visually observed.

Burner A has a nominal grill-to-burner distance of 10.8 mm. For this distance, thermal efficiency is around 50% for the unrestricted case and 53% for the restricted case. In the case of burner B, the nominal distance is 8.3 mm and the corresponding efficiencies are around 54% and 56.5% for the unrestricted and restricted case, respectively. All cases, except burner A with unrestricted primary air, comply with EN 30 minimum thermal efficiency of 52%.

**Emission Indices**

Figures 3 and 4 present the CO Emission Index versus grill-to-burner distance for burners A and B, respectively. It is apparent that the combustion-quenching effect of the cold pot surface, which becomes more important with a decreasing grill-to-burner distance, increases CO emissions. It is also clear that primary air restriction has a larger effect on burner B. This is probably due to a larger restriction in this burner and not to an intrinsic characteristic of the burner itself. It is worth noting that there is a large change in CO emissions from the smallest to the largest distance, in contrast with the modest changes in efficiency. This suggests that
if the goal is to reduce indoor air pollution, it might be well worth sacrificing a bit on efficiency.

CO emission indices for the nominal grill-to-burner distance for burner A can be taken from Figure 3, being around 0.05 g/MJ for the unrestricted case and 0.25 g/MJ for the restricted case. In the case of burner B, the corresponding emission indices for the design distance are around 0.05 g/MJ for the unrestricted case and 0.3 g/MJ for the restricted case.

NO emissions have an opposite behavior to CO, as can be seen in the plots of the NO emission index versus grill-to-burner distance for burners A and B, as shown in Figures 5 and 6, respectively. However, the range of variation of the EI is not as pronounced as in the case of CO. This suggests that the prompt mechanism makes a significant contribution to NO formation because the flame cooling effect of the proximity to the pot does not make such a big difference in NO emissions. Probably most of the NO is produced by the prompt mechanism for the smallest grill-to-burner distance, and the excess NO produced as the distance increases is due to the thermal path. This possibility is also backed by the fact that EI from unrestricted and restricted air cases are very similar when the pot is near the burner. The reduced contribution of the thermal mechanism under these circumstances is likely due both to low temperature and small residence time. It is interesting to observe that for burner B and a large grill-to-burner distance, the unrestricted case produces less NO than the restricted case. It is possible that in this case the primary air ratio is over stoichiometric, producing a low-temperature, lean flame.
For the nominal grill-to-burner distance, burner A shows NO emission indices of around 0.018 g/MJ for the unrestricted case and 0.012 g/MJ for the restricted case, and burner B has around 0.0125 g/MJ for both cases.

The NO\textsubscript{2} mixture ratio was also measured for burner B under unrestricted primary air conditions for the full range of grill-to-burner distances. The results, summarized in Table VI, show that the ratio NO\textsubscript{2}/NO is quite constant and its average can be used to estimate the NO\textsubscript{2} emission index from NO indices. Assuming that this ratio holds for all conditions in this work, NO\textsubscript{2} emission indices...
EMISSIONS FROM A COOKING RANGE

TABLE VI Mixture ratios of NO, NO₂, and NO₂/NO ratio

<table>
<thead>
<tr>
<th>Grill-to-burner distance, mm</th>
<th>NO, ppm</th>
<th>NO₂, ppm</th>
<th>NO₂/NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.31</td>
<td>3.25</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>10.25</td>
<td>4.00</td>
<td>0.39</td>
</tr>
<tr>
<td>10</td>
<td>11.13</td>
<td>4.00</td>
<td>0.36</td>
</tr>
<tr>
<td>15</td>
<td>11.00</td>
<td>2.06</td>
<td>0.19</td>
</tr>
<tr>
<td>20</td>
<td>11.44</td>
<td>4.00</td>
<td>0.35</td>
</tr>
<tr>
<td>25</td>
<td>12.06</td>
<td>2.75</td>
<td>0.23</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.31</td>
</tr>
</tbody>
</table>

FIGURE 7 CO Corrected Emission Index for burner A with restricted and unrestricted primary air entrance.

FIGURE 8 CO Corrected Emission Index for burner B with restricted and unrestricted primary air entrance.
can be estimated by multiplying the corresponding NO index by 0.48. This factor comes from the average NO₂/NO ratio of 0.31 and the molecular weights of NO₂ and NO. NO₂ emissions are more relevant because they represent a higher threat to human health than NO.

As in numerous other combustion applications, here we have the opposite behavior of CO and NO emissions. This presents the problem of finding the best compromise between the opposing emissions. In other words, we need to optimize emissions as a whole. However, there is also another factor that has to be taken

FIGURE 9  NO Corrected Emission Index for burner A with restricted and unrestricted primary air entrance.

FIGURE 10  NO Corrected Emission Index for burner B with restricted and unrestricted primary air entrance.
into consideration-thermal efficiency changes. In order to have all these factors in a single variable, we defined a corrected emission index as the emission index divided by thermal efficiency [Eq. (9)]. Figures 7–10 show this corrected emission factor for CO and NO and the two burners tested.

It seems possible to define a single emission index for all relevant pollutants as the weighed average of the individual corrected emission indices. For this purpose it is necessary to find the weighing factor for each emission index, according to the harm they produce to humans. This single-emission index will constitute the parameter that must be minimized by adjusting the grill-to-burner distance.

**CONCLUSIONS**

A decrease of the grill-to-burner distance has a large effect on the corrected emission indices of CO and a much smaller effect on NO emissions. Indeed, CO-corrected emissions can increase up to two orders of magnitude by only decreasing the grill-to-burner distance from 25 mm to 0 mm. On the other hand, NO-corrected emissions can be reduced up to four times by the same decrease in grill-to-burner distance. The reduction of primary air has a far more moderate effect on CO and NO emissions. Reducing primary air increases CO up to six times and decreases NO by no more than 1.5 times. Efficiency changes follow the same trend as CO, but in a very moderate way. The largest increase in efficiency is less than 1.3 times. Neither maximum nor minimum was found in the studied variables. As expected, NO emissions show a behavior opposite to that of CO emissions.

We suggest using an emission index corrected by efficiency in order to compare emissions under different circumstances. The rationale for this is that what really matters is the useful heat and not the gross heat release. Additionally, we propose to use a combined emission index, calculated as the weighted average of CO- and NO-corrected emission indices in order to optimize the operating conditions in such a way as to produce the minimal harm to human beings.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>nozzle area</td>
</tr>
<tr>
<td>$C$</td>
<td>moles of carbon per mole of fuel</td>
</tr>
<tr>
<td>CEI</td>
<td>corrected Emission Index based on heat released</td>
</tr>
<tr>
<td>$C_p$</td>
<td>constant pressure specific heat</td>
</tr>
</tbody>
</table>
$D$ pot diameter

$D_{\text{used}}$ pot diameter actually used

$D_{\text{recomm}}$ pot diameter recommended by EN 30

$\text{EI}$ Emission Index based on heat released

$\text{EI}_m$ Emission Index based on the fuel mass

$\text{HHV}$ high heating value

$K_N$ nozzle flow coefficient

$m_f$ fuel mass flow

$m_f^*$ mass of fuel consumed in the efficiency test

$m_w$ water mass in the pot

$\text{MW}_f$ fuel molecular weight

$\text{MW}_i$ molecular weight of component $i$

$p_1$ gas pressure before nozzle

$p_2$ gas pressure at the exit of the nozzle

$\dot{Q}$ heat release rate

$S$ pot bottom section

$T_c$ thermal consumption or heat release rate

$T_1$ water initial temperature

$T_2$ water final temperature

$X_i$ mole fraction of component $i$

$X_{\text{CO}_2}$ mole fraction of $\text{CO}_2$

$X_{\text{CO}}$ mole fraction of $\text{CO}$

$X_{\text{CO}_2}^i$ mole fraction of $\text{CO}_2$ produced on a stoichiometric ideal combustion

$X_{\text{O}_2}$ mole fraction of $\text{O}_2$

$\eta$ thermal efficiency

$\rho$ fuel density.

References


