Rapport SGC 121

Catalytic combustion in gas stoves – feasibility study

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Rapport SGC 121 • ISSN 1102-7371 • ISRN SGC-R--121-SE

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Summary

A feasibility study concerning the possibilities to replace flame combustion with catalytic combustion in gas stoves has been conducted on the request of Swedish Gas Centre (SGC). The feasibility study gives an introduction to the problems associated with indoor emissions of nitrogen oxides (NO_x).

Several independent studies show that gas stoves to some degree contribute to the indoor emissions of NO_x, especially in situations were the ventilation flow is poor. The peak-NO_x-concentrations can reach several hundred ppb but the integral concentration seldom exceeds about 20 – 50 ppb, which corresponds to an indoor-outdoor ratio of about 1 – 2.5. Epidemological studies indicate increasing problems with respiratory symptoms in sensitive people at concentrations as low as 15 ppb of $NO_{x.}$ Consequently, the NO_x-concentration in homes where gas stoves are used is high enough to cause health effects. However, in situations where the ventilation flow is high (utilisation of ventilation hoods) the NO_x-emissions are not likely to cause any health problems.

The feasibility study suggests a number of design solutions for catalytic gas stove burners. The simplest types are suitable for retrofit installation in atmospheric burners whereas the more sophisticated types need an assisting fan for the air supply.

Introductory experiments with catalytic wire meshes and catalytic coils installed downstream the flame ports of the burner, indicate a great potential for NO_x-reduction without increasing the emissions of CO or decreasing the thermal efficiency. Indeed, the NO_x-emissions can be reduced by more than 95% by replacing conventional flame combustion with catalytic combustion. Thus, the NO_x-problem can be resolved by a simple, durable and cheap design modification including a combustion catalyst.

The impact on the indoor NO_x-concentration is evident from dynamic simulations; catalytic combustion will eliminate the problem with respiratory symptoms associated with indoor NO_x arising from gas stoves.

It is now important to carry out comprehensive studies concerning emissions and thermal efficiencies for different design suggestions. Design optimisation as well as extensive durability tests will also be carried out in the following-up study, planned for 2002. However, since the mechanic durability of the catalyst is good, a number of methods to clean the catalyst are possible, e.g. through washing.

Sammanfattning

En förstudie avseende möjligheterna att ersätta konventionell flamförbänning med katalytisk förbränning i gasspisar har genomförts på uppdrag av Svenskt Gastekniskt Center AB (SGC AB). Förstudien ger en introduktion kring de problem som förorsakas av utsläpp av kväveoxider (NO_x) inomhus.

Ett flertal oberoende studier visar att användning av gasspisar i viss grad bidrar till en ökad halt av NO_x inomhus, speciellt i de fall då ventilationsflödet är bristfälligt. Den maximala halten kan uppgå till flera hundra ppb men medelhalten överstiger sällan 20 – 50 ppb, vilket motsvarar ett haltförhållande mellan inomhus- och utomhusluften på 1 – 2.5. Epidemologiska undersökningar visar samtidigt att en varaktig ökning av NO_x-halten på 15 ppb medför respiratoriska symptom hos känsliga personer. Användning av gasspisar medför således en tillräckligt stor ökning av NO_x-halten för att hälsoeffekter skulle kunna uppstå. Om ventilationsflödet är tillräckligt stort (utnyttjande av spisfläkt) reduceras dock problemen i väsentlig grad och härvid förväntas hälsoeffekterna bli försumbara.

I förstudien föreslås ett antal designalternativ avseende katalytiska brännare. De enklaste typerna är lämpliga för installation i konventionella atmosfäriska brännare medan de mer komplexa alternativen kräver fläkt för lufttillförseln.

Inledande förbränningsförsök med katalytiska nät och spiraler visar att NO_x- emissionerna kan reduceras i väsentlig grad jämfört med konventionell förbränning utan att CO-emissionerna ökar eller att den termiska verkningsgraden minskar. Försöken visar att NO_x-emissionerna kan reduceras med mer än 95% genom en enkel, hållbar och billig designförändring som innefattar en förbränningskatalysator.

Inverkan på inomhusluftens kvalitet framgår med tydlighet från dynamiska simuleringar; katalytisk förbränning eliminerar de problem med respiratoriska symptom som i vissa studier sammankopplas med användning av gasspisar inomhus.

Det är nu av vikt att genomföra omfattande studier avseende emissioner och termiska verkningsgrader för de olika designförslagen. Förutom dessa moment kommer designoptimering och studier avsseende katalysatordeaktivering att ingå i fas 2 av detta projekt, vilket planeras genomföras under 2002. Eftersom den mekaniska stabiliteten hos katalysatorn är god kommer den att kunna rengöras på olika sätt, t.ex. genom sköljning.

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1. Introduction

Utilisation of open gas flames for heating and cooking results in indoor emission and dispersion of hazardous components like carbon monoxide (CO), unburned hydrocarbons (UHC) and nitrogen oxides (NO_x). A number of studies have been conducted over the years to analyse and quantify the detrimental health effects of these emissions. Indeed, indoor emissions of NO_x are correlated to the development of respiratory diseases, as shown in a number of independent studies. Also a rather modest increase in the indoor NO_x-concentration is expected to cause an increased predisposition for respiratory symptoms.

Extensive studies have been conducted to quantify the contribution of gas stove emissions to the overall average indoor concentration of NO_x. The gas stove contribution is dependent upon several factors like:
- emissions rate of NO_x (source strength)
- ventilation flow (presence/absence of ventilation hood)
- room design
- background concentration (outdoor concentration of NO_x)

The utilisation of gas stoves follows a discontinuous pattern and the indoor NO_x-concentration will consequently vary during the day. To predict the detrimental effects of gas stove emissions, it is essential to develop tools to predict the build-up and decay of the indoor NO_x-concentration. These calculations are normally performed with dynamic simulation tools where the kitchen is modelled as a continuous stirred tank reactor (CSTR) or a three-dimensional reactor (TDR, suitable for computational fluid dynamics). These simulations will present predictions of the average NO_x-concentration versus the time. The TDR-model also presents data concerning the NO_x-concentrations at special positions within the kitchen.

From previous studies, however, it is clear that the most important factor for the concentration build-up is the source strength (the emission rate of NO_x). It is also evident that rather high source strengths are acceptable if the ventilation flow is high enough. This is normally the case when ventilation hoods are installed.

This report describes measures to reduce the harmful NO_x-emissions from conventional gas stoves, i.e. to reduce the source strength through catalytic combustion. Catator AB has developed a wire-mesh catalyst suitable for retrofit-installation in atmospheric burners. The wire-mesh catalyst is characterised by high mass-and heat transfer capacities, a high intrinsic catalytic activity and an extremely low pressure drop. In addition, the wire-mesh catalyst has a high degree of geometric flexibility, which is of importance in this application.

The report covers different design suggestions and some introductory combustion experiments performed on a gas stove (IGF-Kavalkad). In addition to the NO_x-emissions it is important also to study possible effects on the CO-emissions and the thermal efficiency of the cooking plates when replacing conventional flame combustion with catalytic combustion.

A dynamic simulation model (CSTR-model) is used to evaluate the consequences on the indoor air quality. The design solutions will be evaluated and optimised in a following-up study.

2. Objectives

The overarching objective of this feasibility study is to suggest possible design solutions concerning catalytic burners in gas stoves. It is important to develop simple, durable and cheap solutions for retrofit installations as well as for new stove designs. This study is not an experimental study although some introductory experiments are conducted. A dynamic simulation model is developed to analyse the consequences of catalytic combustion on the indoor air quality. Comprehensive experimental investigations as well as optimisation studies are planned for a following-up project.

Thus, the objective of the feasibility phase might be expressed as:

"To evaluate the possibilities of catalytic combustion in gas stoves and to suggest different design solutions for implementation of catalytic burners in gas stoves".

3. Background information

The environmental consequences of NO_x-emissions are well-known. Nitrogen oxides are strongly irritating and contribute together with hydrocarbons in the production of photochemical smog. NO_x is generally emitted in the form of nitrogen oxide (NO) but is slowly oxidised into nitrogen dioxide (NO_2) at ambient conditions. The reported respiratory symptoms are attributed to NO_2-exposition. The total NO_x-emission is considered to be in the form of NO_2 in most studies to adopt a conservative attitude to the problem.

The outdoor concentration of NO_2 in urban areas is typically below 40 $\mu g/m^3$ (20 ppb). The actual outdoor concentration might vary considerably due to the traffic situation and the existence of other major sources in the surroundings. The indoor concentration is considerably lower than the outdoor concentration since NO_2 has a tendency to react on walls, furniture's and other surfaces.

In a study presented by Garrett et. al., the indoor median concentration of NO_2 varied between 6.0 and 128 ppb [1]. The major contributors to the nitrogen oxides were gas stoves, vented gas heaters and smoking. A similar study performed by Levy et. al. indicate indoor mean-concentrations of 11.0 – 51.5 ppb NO_2 with a 67% increase in mean personal NO_2 exposure and an increase in indoor-outdoor ratios from 0.7 to 1.2 when using gas stoves [2]. Quackenboss et. al. showed that the indoor NO_2-concentration was 9 to 18 ppb higher than the corresponding outdoor-concentration in homes where gas stoves were used [5]. Utilisation of gas stoves also increases the exposure to CO, as indicated by S. Alm et. al. [3].

Epidemological studies on the effects of indoor NO_2 showed that a 17 ppb increase of the annual average NO_2-level was associated with an increased prevalence of five different respiratory symptoms [4]. A similar study by Hasselblad et. al. indicates that the odds of respiratory illness in children exposed to long-term increase of about 15 ppb NO_2 is 20% [6].

In a theoretical study presented by Stymne the calculated mean concentration of NO_2 following normal gas stove utilisation is typically below the outdoor concentration (7 – 20 ppb) [13]. The indoor concentration will exceed the outdoor concentration only in situations with very poor ventilation or when no ventilation hood is installed. A similar investigation performed by

Jensen et. al. indicates a possibility of much higher NO_2-levels, especially in situations with a poor ventilation flow [14]. At a height of 170 cm (head level) the average NO_2-concentrations (measured during 1 h) vary between 20 and 750 ppb. The mean-concentration of NO_2 considering the whole kitchen (CSTR-approximation) vary between 20 and 100 ppb. It is surprising that these studies present so different results. The input data and the model assumptions differ somewhat but the main reason is attributed to differences in the anticipated source strength. According to Jensen et. al. the source strength is 90 – 120 mg NO_2/kWh (51 – 68 ppm) whereas Stymne uses a value of 36 mg/kWh (21 ppm). According to our investigations, the NO_2-source strength is above 60 ppm, which corresponds to the findings by Jensen et. al.. If the results presented by Stymne are re-calculated with this higher source strength, we obtain a fair correlation with the results presented by Jensen et. al. These calculated values are also in agreement with the empirical results presented above [1, 2 and 5]. Consequently, if the input data and model assumptions are realistic, we obtain a fair correlation between the calculations and the empirical investigations.

If the epidemological studies concerning health effects of NO_2-exposure are evaluated in the light of the gas-stove related NO_2-emissions, it is clear that sensitive persons may develop respiratory illnesses and symptoms. However, effective ventilation and installation of ventilation hoods will decrease and possibly eliminate these possible health effects.

4. Earlier work

NO_x-emissions are associated with flame combustion, where the combustion temperature is high enough to cause formation of prompt and thermal NO_x. The equilibrium between NO and NO_2 is strongly shifted towards NO at these temperatures and more than 70% of the NO_x-emission is in the form of NO. Thermal NO_x is a fixation of atmospheric nitrogen and oxygen whereas prompt NO_x originates from radical reactions between hydrocarbon species and nitrogen.

NO_x-production in atmospheric burners shows a maximum at 40 - 50% primary aeration, which is typical for burners in gas stoves. The source strength (emission rate) is typically 100 mg/MJ or more of NO_2 (equal to about 50 - 60 ppm at stochiometric conditions). The NO_x-emissions can be reduced through installation of burners with a higher degree of primary aeration [7]. By adjusting the area ratio between the nozzle and flame ports it is possible to arrive at full aeration. By doing this the NO_x-emissions can be reduced by 25 - 50%.

A number of design solutions to overcome the emission problems have been presented over the years. By utilising two-stage combustion it was possible to reduce the emissions of NO_x and CO by 90% and formaldehyde by 70% [8].

In order to arrive at still lower emissions it is necessary to use catalytic combustion. Several studies utilising ceramic monoliths in pre-mixed combustion have been presented (Gasunie/Gastec). The NO_x-emissions are typically close to zero but the complexity of the system has hindered commercialisation. A number of patents concerning ceramic and fibrous burners have been presented [e.g. 9 – 12]. The experiences concerning NO_x-emissions are generally good but design- and durability problems are serious issues, which have not been successfully resolved yet.

Also, the stove industry, like the boiler industry, is extremely conservative and it takes considerable time for such business to adapt to new concepts, even if successful.

The challenge is to design/develop a catalyst/catalytic burner, which is simple, durable and cheap. The catalyst shall preferably be easy to install in existing atmospheric burners without too much re-design work. The wire-mesh approach opens possibilities for direct utilisation in atmospheric burners due to an extremely low pressure-drop. The high intrinsic catalytic activity in combination with excellent mass-and heat transfer capacities enable us to design compact catalytic burners with superior start-up characteristics.

5. Catalytic combustion – principles

Catalytic combustion is a surface reaction, where the gas components diffuse into the catalyst, adsorb on to the catalyst and react. Activation of the molecules is primarily through chemisorption, which facilitates low combustion temperatures in comparison to conventional flame combustion. Due to the “cool” combustion, the rate of NO_x-formation is extremely low. Thus the NO_x-emissions can be as low as 1 ppm or less (see Figure 1). When increasing the load to values above about 600 kW/m^2 (calculated on the cross sectional area), the combustion capacity of the catalyst is too small to facilitate complete combustion. However, the catalyst will produce reactive radicals, which are emitted into the gas phase where the majority of the combustion will occur. Thus hybrid combustion will occur at loads between 600 and 1200 kW/m^2 and associated NO_x-emissions are typically between 1 and 10 ppm. If the load is increased to still higher values, we arrive at blue-flame combustion, characterised by rather high NO_x-emissions (typically above 30 ppm).

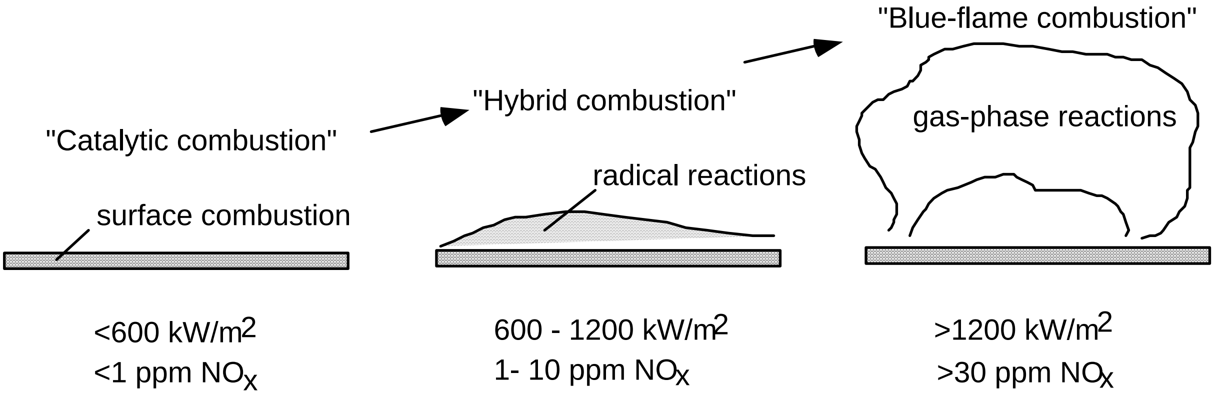
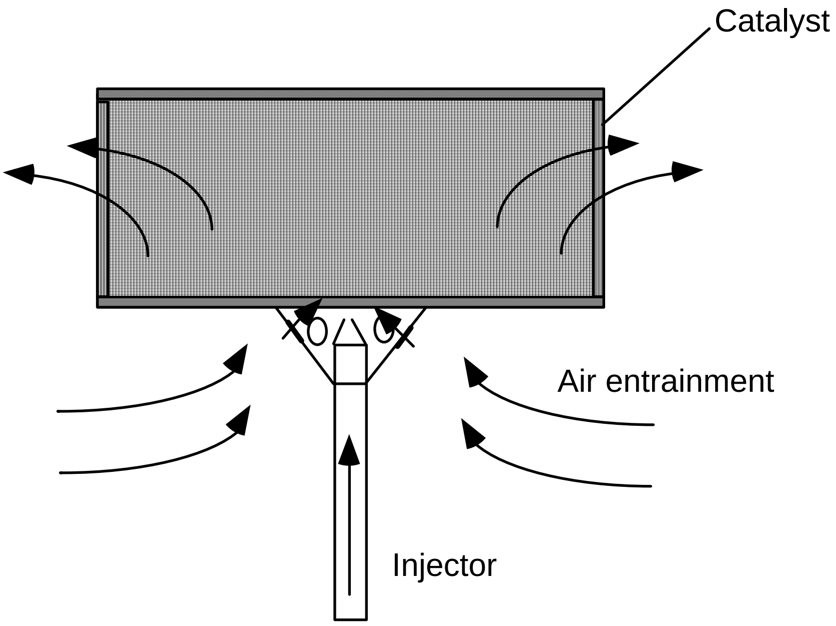


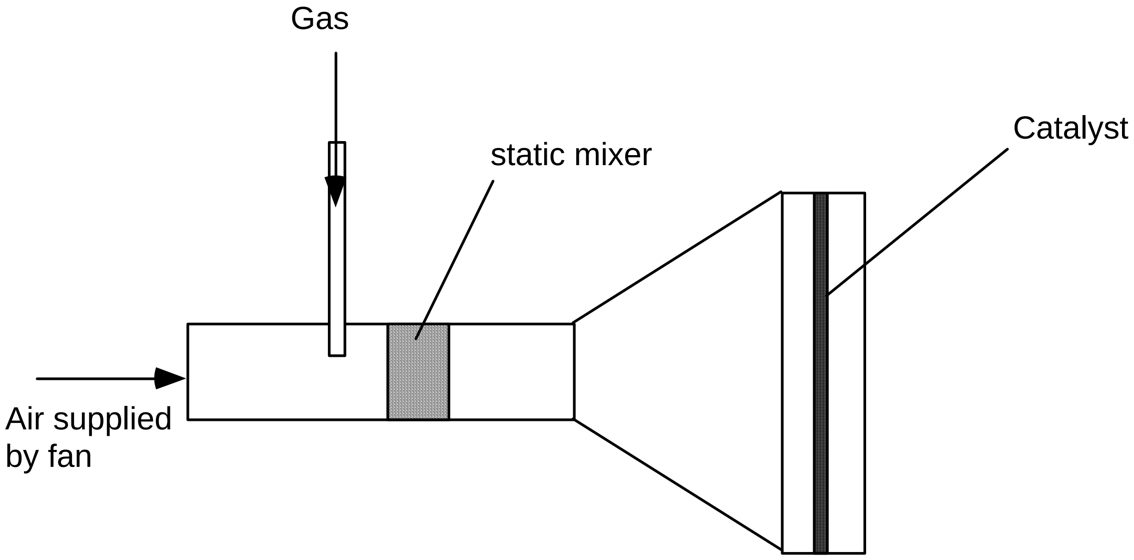
Figure 1 Combustion mechanisms

A combustion catalyst shall operate at loads below 1200 kW/m^2 in order to work properly and to facilitate effective NO_x-reduction. Thus, the amount of combustion catalyst necessary will typically lie in the interval 0.1 – 1 dm^2 per cooking plate.

Figure 2 shows the fundamental differences between atmospheric combustion and fully pre-mixed combustion. In atmospheric combustion, the necessary combustion air is supplied via an injector, powered by the gas jet. It is possible, although not common, to design the nozzle and flame ports for full aeration. The degree of primary aeration is typically between 40 and 70%. The turn-down ratio of atmospheric burners is wide, typically 1:5 or more. By replacing the conventional flame ports with a catalytic wire-mesh catalyst it is possible to design a catalytic atmospheric burner, characterised by low emissions and an even wider turn-down ratio (less problems with flame lift at high loads).



Atmospheric combustion



Pre-mixed combustion

Figure 2 Main group of burners

Pre-mixed burners are normally used in condensing boilers where the air flow is assisted by a fan. By installing a catalyst downstream the mixing zone it is possible to design a pre-mixed catalytic burner. Gastec has investigated such burners in gas stove applications with a monolith catalyst [15]. Pre-mixed burners are more complicated than atmospheric burners but are less sensitive to disturbances. The catalytic burner might be located under an IR-transparent ceramic plate and the flue gases can be vented directly to the atmosphere, i.e. the problems with indoor emissions are eliminated. However, the thermal response of the cooking plate will be much lower than in an open system, which is a serious disadvantage.

6. Emission mapping of a conventional gas stove and possible consequences on indoor air quality

In order to get appropriate data for modelling purposes, the raw emissions of NO_x and CO were measured in a commercial stove (IGF-Kavalkad). The emissions were measured with a pan on the cooking plate. We also estimated the thermal efficiency of the cooking plate from experiments with water heating.

The source strength of NO_x ($NO + NO_2$) was about 135 mg/kWh, which is in fair agreement with the values presented by Jensen et. al. [14]. The source strength of CO was about 10 times higher, 1100 mg/kWh. The CO-emission was much lower when the cooling pan was removed from the cooking plate.

A differential material balance of a kitchen (CSTR-approximation) was set up according to:

$F_0C_0(1-\eta) + (F_v + F_i)C_{out} + k_dC_rV_r = (F_0\eta+F_v+F_i)C_r + V_rdC_r/dt$, where:

F_0=Burner flow (nm^3/h), [F_0=f(time), see below]
C_o=Concentration at flame port (ppm), [C_o=75 ppm of NO_2, 500 ppm of CO]
η=Capture efficiency of hood, [η=0.7]
F_v=Forced ventilation flow (nm^3/h), [F_v=200 nm^3/h, only in operation when the gas stove is used]
F_i=Infiltration flow (nm^3/h), [F_i=15 nm^3/h]
C_{out}=Outdoor concentration(ppm), [C_{out}=20 ppb]
k_d=First order decay rate (h^{-1}), [k_d=-0.5 h^{-1}]
C_r=Average concentration in kitchen (ppm), [C_r is calculated]
V_r=Room volume (m^3), [V_r=30 m^3]
dC_r/dt=Concentration change (ppm/h), [dC_r/dt is calculated]

The concentration changes were simulated during a day (24 h) when the gas stove was used according to the scheme presented by Stymne [13], see Table 1 below:

Table 1, Utilisation pattern according to Stymne [13]

Activity	Duration (time)	Effect (kW)
Coffee	07.00 – 07.05	3
Coffee	09.30 – 09.35	3
Boiling	11.30 – 11.40	3
Boiling	11.40 – 11.50	0.5
Boiling/broiling	11.50 – 12.00	3.5
Coffee	12.15 – 12.20	3
Coffee	15.00 – 15.05	3
Boiling	17.30 – 17.35	3
Boiling	17.35 – 17.45	0.5
Broiling	17.45 – 17.50	3
Coffee	18.10 – 18.15	3
Tea	21.00 – 21.05	3

Figure 3 shows the concentration variations during one day's use of a conventional gas stove. The peak concentrations are obtained at lunch (1.7 ppm of CO and about 0.2 ppm of NO_2). Since we are using a higher source term than Stymne, we also arrive at considerably higher NO_2-concentrations in the kitchen.

It is also of interest to calculate the integral dosage of NO_2 during the whole day. These calculations indicate a indoor-outdoor ratio of 2 – 2.5, i.e an average increase of about 20 ppb which is in good agreement with empirical studies [1-2, 5]. According to epidemological data, this dosage might give rise to respiratory symptoms in sensitive persons. The dosage is decreased by the following measures:
- Decrease the source strength, e.g. install catalytic combustion
- Increase the ventilation flow
- Improve the capture efficiency of the ventilation hood

This study focuses on catalytic methods to decrease the source strength. A number of different design solutions are suggested in the next chapter. The design suggestions refer both to retrofit installations and to new stove designs.

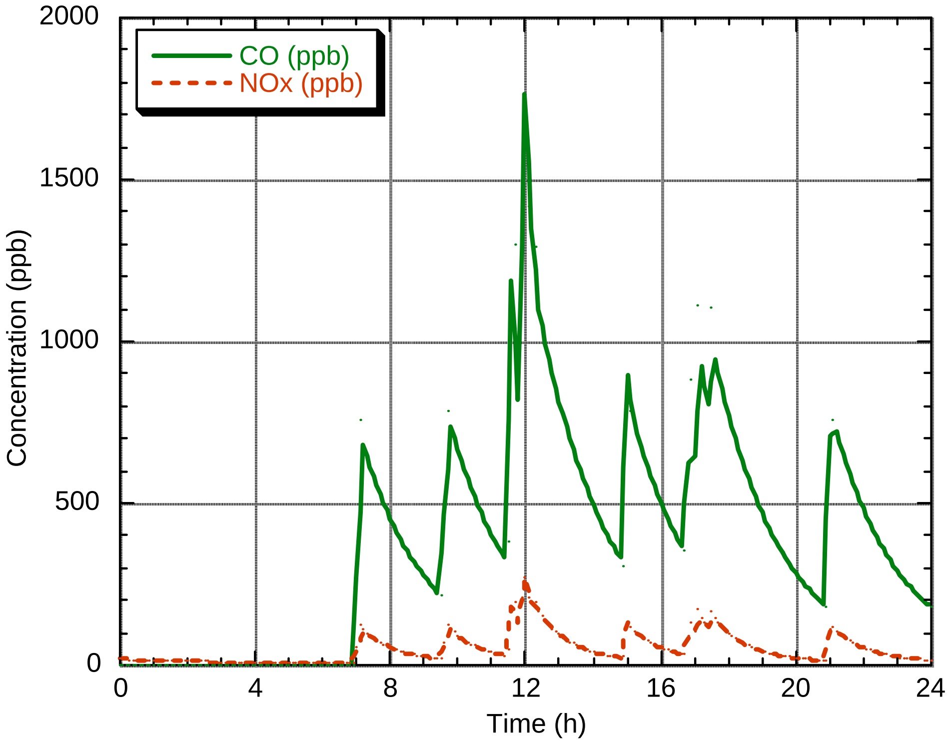


Figure 3 *Typical concentration pattern of CO/NO$_x$ during one day. The values are based on calculations according to Table 1.*

7. Design solutions

The simplest way of introducing catalytic combustion in gas stoves is to use the existing burners and to modify these. The conventional burners use injectors for the air supply. Such atmospheric burners are highly sensitive to pressure variations downstream the burner. The fuel- to air ratio will vary considerably with the pressure drop in the system. The burners are normally designed for a primary aeration of about 40-70%, which means that secondary combustion will take place downstream the flame ports.

If the flames impinge on cool surfaces (like a pan), CO is likely to be formed and emitted. Indeed, our experiments indicated a dramatic rise in the CO-emissions when putting a pan on to the cooking plate.

In principle, it is possible to arrive at full aeration by increasing the ratio between the flame port area and the nozzle area. However, the sensitivity to flashback is likely to increase due to lower exit velocities and larger flame ports.

Figure 4 shows a schematic drawing of a conventional atmospheric burner for stove applications. The diameter of the injector nozzle is adjusted to the gas quality, i.e. the Wobbe index of the fuel gas.

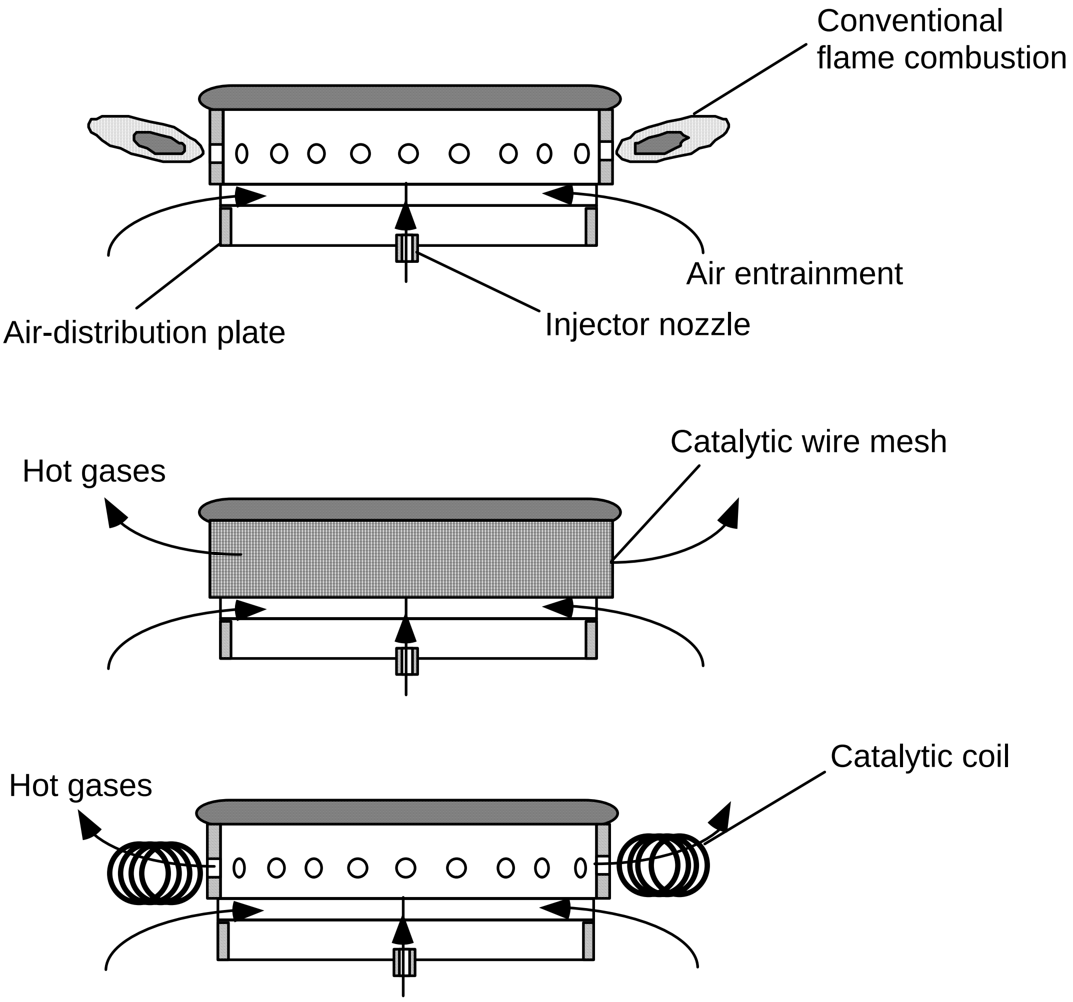


Figure 4 Retrofit installations

By placing a catalytic wire-mesh downstream the flame ports it is possible to quench the flames and to obtain a mixture between flame combustion and catalytic combustion. The NO_x-emissions can be reduced by more than 50% but the CO-emissions are likely to increase.

Another alternative is to replace the flame port plate with a wire-mesh catalyst, to enable full catalytic combustion, see Figure 4. The NO_x-emissions will be close to zero and the CO-emissions are easier to control. In still another design suggestion a catalytic coil is placed downstream the flame port area for flame quenching. Again, the NO_x-emissions are likely to decrease to very low values but the CO-emissions might cause problems. The alternatives using catalytic wire meshes and catalytic coils are indeed easily realised, also in conventional gas stoves.

It might be necessary to change the nozzle diameter in order to increase the degree of primary aeration. This measure will ensure lower CO-emissions.

Figure 5 shows another design suggestion of a catalytic cooking plate. In this design an atmospheric mixer is used but the flow direction is vertical rather than horizontal. The surface load (kW/m^2) is lower in comparison to the alternatives presented in Figure 4, which will enable even lower NO_x-emissions.

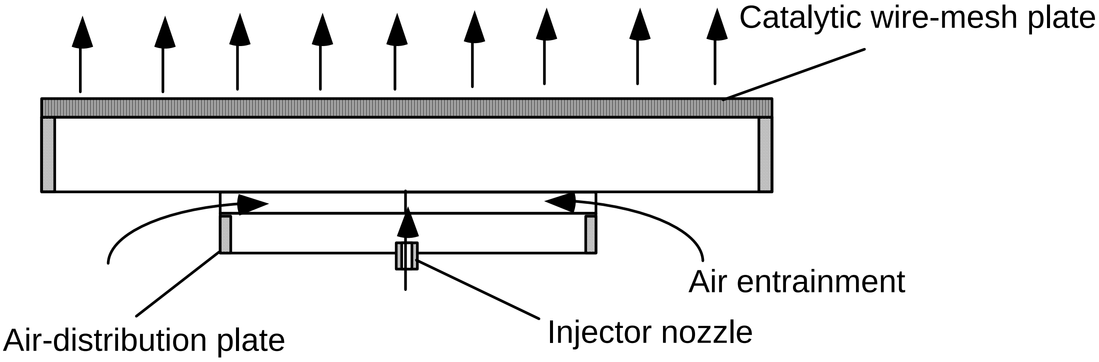


Figure 5 Pre-mixed plate

A more novel design suggestion is presented in Figure 6. This burner design utilises premixed air and fuel. The air is supplied with a fan and the fuel- to air ratio is controlled automatically via a valve system. Since the burner operates under a higher pressure than the atmospheric burners the flue gases might be vented directly to the atmosphere, i.e. no indoor emissions of NO_x. The pre-mixed gas is led through one concentric layer of the catalyst for combustion and through a secondary catalyst for possible flue-gas purification with respect to UHC and CO. The thermal response will be lower than in the alternatives presented in Figures 4 and 5, due to a higher thermal inertia. Also, the burner is covered with an IR-transparent ceramic plate, which will add thermal inertia. Implementation of catalytic combustion according to this design alternative is more for environmental concern since it is possible also to vent emissions from flame combustion to the atmosphere. It is only when the flue gases are emitted directly into the kitchen that we will see positive health effects of catalytic combustion. The design suggestion will, however, give extremely low emissions of NO_x, CO and UHC even if the quick thermal response, characteristic for gas stoves, is lost.

The next chapter will present data from introductory experiments with design alternatives according to Figure 4. The combustion catalysts are prepared from wire meshes coated with a ceramic layer (alumina) according to Catator’s technology. Palladium is used as the active material since it has a high activity for methane combustion and will survive the thermal impact without vaporisation. The surface load shall be below 1200 kW/m^2 to enable an effective NO_x-reduction. The amount of catalyst will typically be between 0.1 and 1.0 dm^2 per cooking plate.

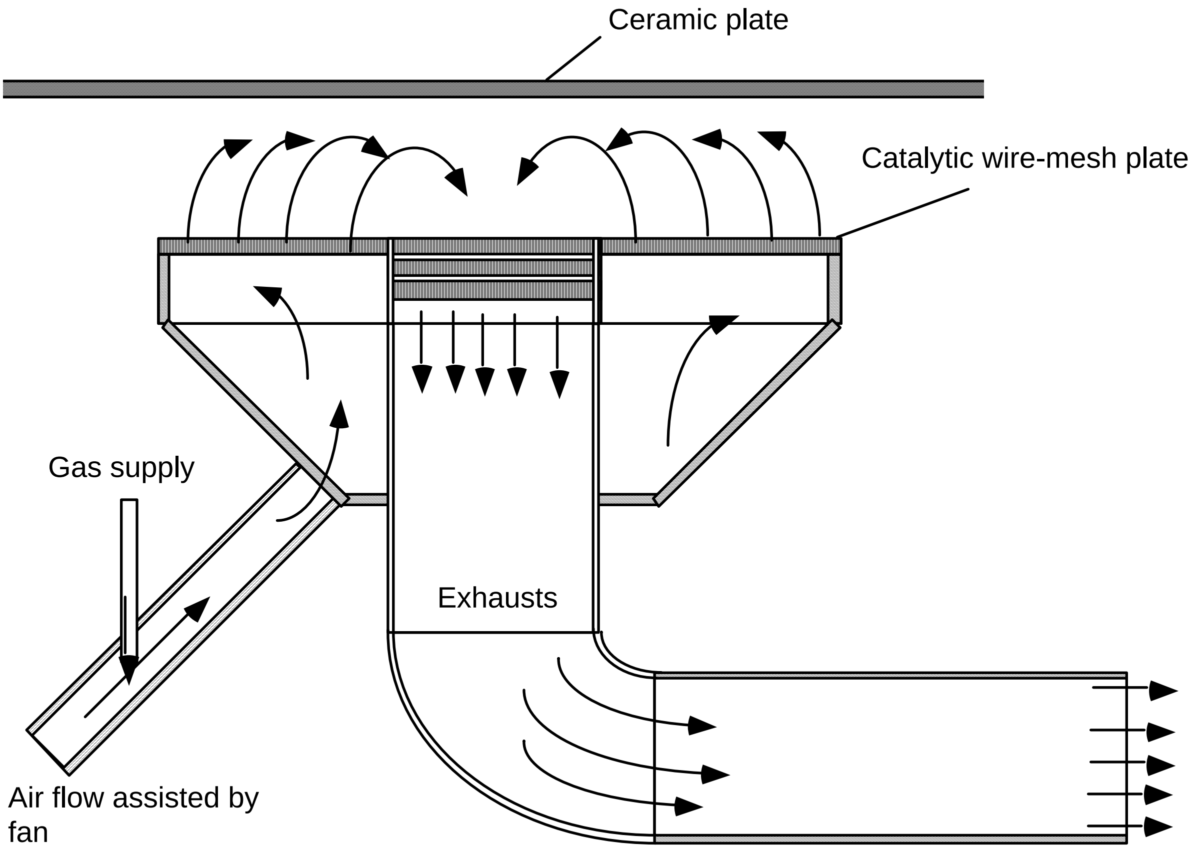


Figure 6 Pre-mixed plate covered with ceramics

8. Introductory experiments

A number of introductory experiments were performed in a commercial gas stove (IGF-Kavalkad), adjusted for natural gas combustion. A hood was placed above the gas stove to collect and dilute the primary flue gases. Emission measurements were performed at the exhaust pipe and the raw emissions could be calculated from emission data and the dilution factor. NO_x and oxygen were measured by means of an electrochemical device. The NO_x-signal was calibrated with test gases containing known concentrations of NO_x. CO, CO_2 and UHC were measured by means of NDIR-technique. Also the NDIR-instrument was calibrated with test gases.

The thermal efficiency was estimated from tests with water heating. I kg of water was heated from room temperature (20°C) to 100°C. We measured the time necessary to reach 100°C at full power. By comparing the theoretical time to heat the water with the experimentally obtained time, we were able to calculate the thermal efficiency of the cooking plate. The absolute value of the thermal efficiency can vary due to the choice of cooking plate and pan.

The gas stove is fitted with four different cooking plates, ranging from 1.0 to 3.0 kW. No experiments were performed with the oven burner in this study. However, Catator has previously developed catalytic rod burners, which might be utilised in this application.

Table 2 summarises the alternatives, which were evaluated. Experiments with ordinary flame combustion show that the source strength of NO_x corresponds to a value of about 135 mg/kWh. This value is in fair agreement with the values presented by Jensen et. al. [14]. The corresponding CO-source strength was about 1000 mg/kWh when a pan was on the cooking plate. When the pan was removed this value was about 10 times lower. Consequently, CO is primarily formed due to flame impingement on to the cool pan.

Table 2 Tests performed in the gas oven

Notation	Test performed
Without modification	Ordinary flame combustion
wmc #1	Wire-mesh ring downstream flame port plate
wmc #2	Wire-mesh plate above flame port plate
wmc #3	Wire-mesh ring replaced the flame port plate
Metal coil	Metal coil downstream flame port plate
cc#1	Catalytic coil downstream flame port plate, coating #1
cc#2	Catalytic coil downstream flame port plate, coating #2

Figure 7 summarises the experimental findings concerning source strengths of NO_x. All catalytic alternatives enabled a radical decrease of the source strength. Also the inactive metal coil was able to reduce the NO_x-emissions, primarily due to flame quenching and flame cooling. Indeed, the NO_x-emissions could be decreased by 50% in this extremely simple way. Unfortunately, we obtained problems with CO-emissions instead with this solution, which will be described further on.

Best results were obtained when the flame port plate was exchanged with a wire-mesh catalyst and in the alternatives with catalytic coils downstream the flame port plate. In these cases the NOx-emissions were decreased by 92 – 98%. Such low NO_x-emissions are not likely to cause any health problems, not even in situations with a poor ventilation flow.

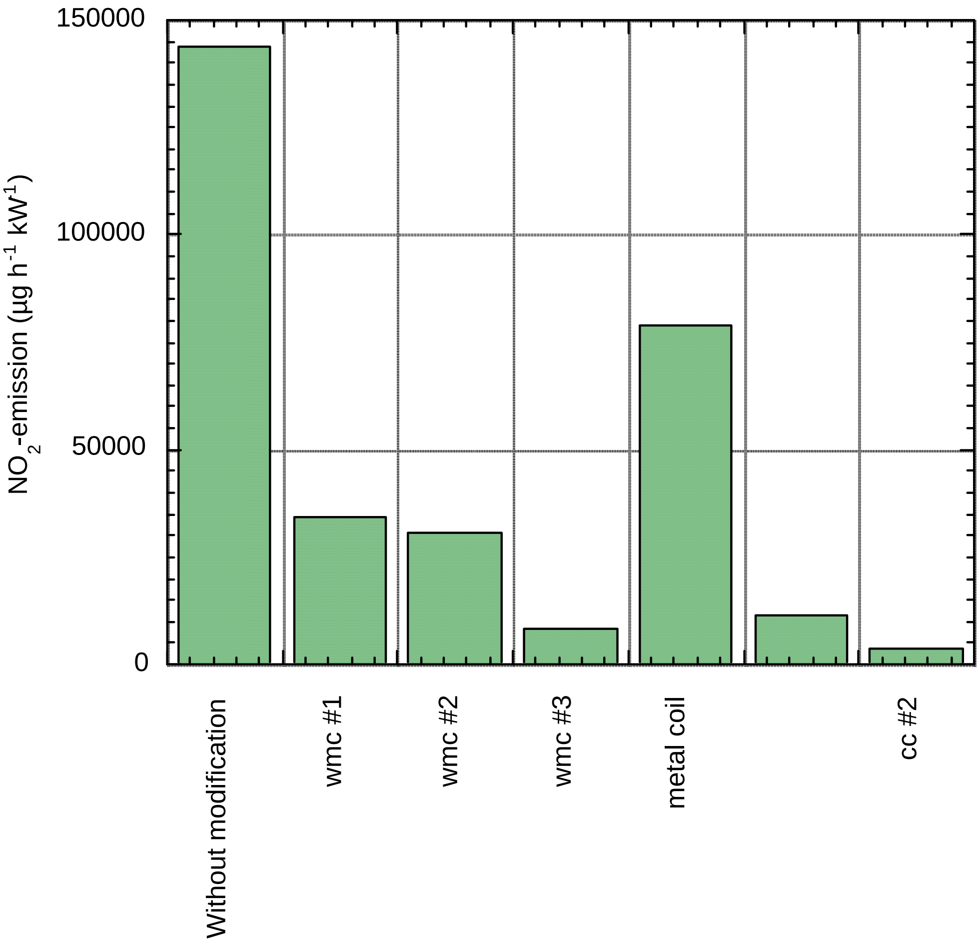


Figure 7 Preliminary results concerning NO_x-emissions

It is also of importance to analyse the effects on the CO-emissions. The source strength of CO was about 1000 mg/kWh with flame combustion (Figure 8). Similar measurements with catalytic combustion (with a pan on the cooking plate) showed that the CO-emissions increased in several cases. Indeed, the CO-emission was increased by 5 – 6 times in some cases, primarily due to incomplete combustion caused by a defective design. The metal coil, which enabled a 50% reduction of the NO_x-emissions, increased the CO-emissions by a factor 6. However, the most effective catalytic design solutions concerning NO_x-reduction also showed a tendency to decrease the CO-emissions. These alternatives decreased the CO-emissions by a factor 50% in relation to ordinary flame combustion. It is probable that the CO-emissions can be reduced further, following a design optimisation. However, the experiments show that it is possible to decrease the NO_x-formation without increasing the CO-formation.

The combustion was effective in all cases. No traces of UHCs could be detected in the experiments.

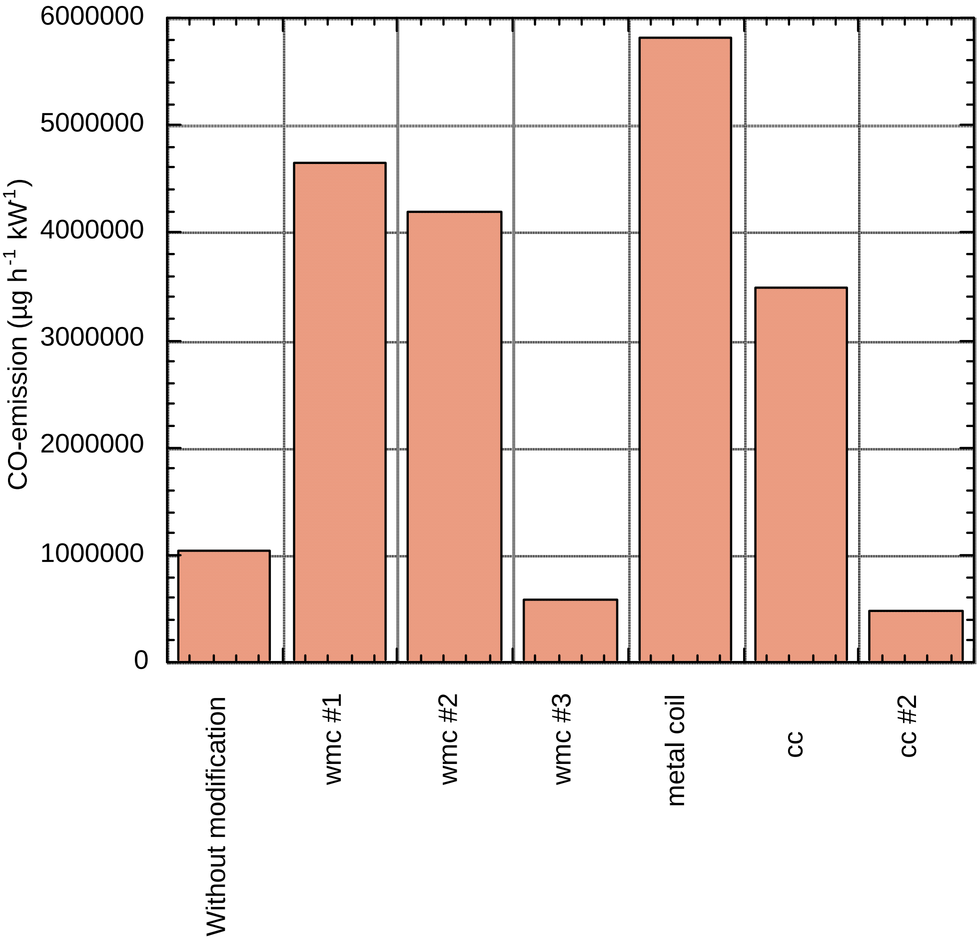


Figure 8 Consequences on CO-emissions

The thermal efficiency is expected to be rather low since very much of the hot flue gases will pass by the pan. Measurements with water heating indicated a thermal efficiency of about 35% when flame combustion was used. The absolute value of the thermal efficiency is, of course, dependent upon the geometric combinations of the pan and the cooking plate. Consequently, this figure might be higher as well as lower. In these tests, however, we used the same set-up to be able to pinpoint possible differences between the alternatives.

Surprisingly enough, all the catalytic alternatives increased the thermal efficiency by 5 to 10%, probably attributed to effects of thermal radiation, see Figure 9. Thus, the results indicate that it is possible to decrease the emissions of NO_x and CO and to simultaneously increase the efficiency of the heat recovery.

The data presented in this study are only relates to introductory experiments. The performance will be improved further through optimisation. Indeed, catalytic combustion may eliminate the problem with indoor emissions and simultaneously add comfort advantages (improved thermal response and a better fuel economy).

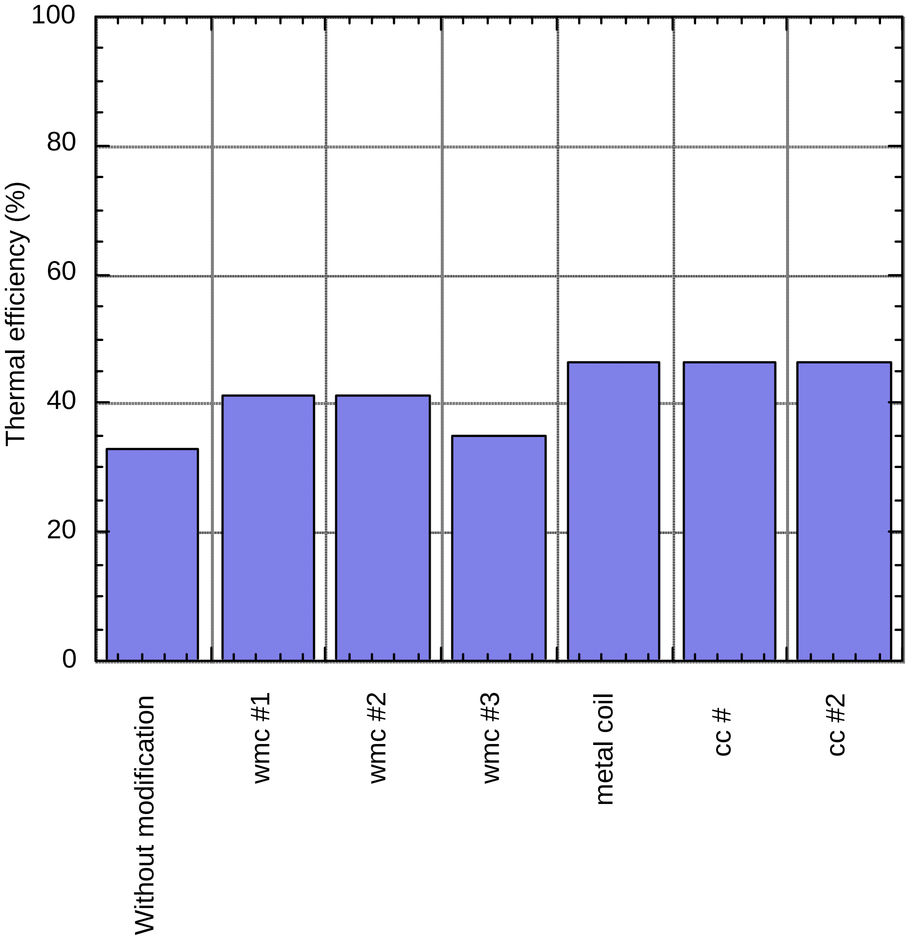


Figure 9 Thermal efficiency

9. Consequences

It is reasonable to expect a strong correlation between the source term of NO_x in the CSTR-model and the indoor NO_x-concentrations. Computer simulations were performed with the source strengths obtained in the experimental study, i.e. 135 mg/kWh for flame combustion and 4 mg/kWh for catalytic combustion. The simulations were based on the utilisation pattern given in Table 1. All parameters were the same as in previous simulations (see page 6).

When conventional flame combustion is utilised, we expect to reach NO_x-concentrations as high as 500 $\mu g/m^3$ (about 250 ppb), see Figure 10. The peak concentrations coincide with lunch activities.

If catalytic cooking plates are used, however, the maximum NO_x-concentration will be about 40 $\mu g/m^3$ (20 ppb), which corresponds to the anticipated outdoor concentration of NO_x. This means that persons in homes utilising catalytic gas stoves never will be exposed to NO_x-concentrations higher than the corresponding outdoor levels. Consequently, no impact on human health is expected.

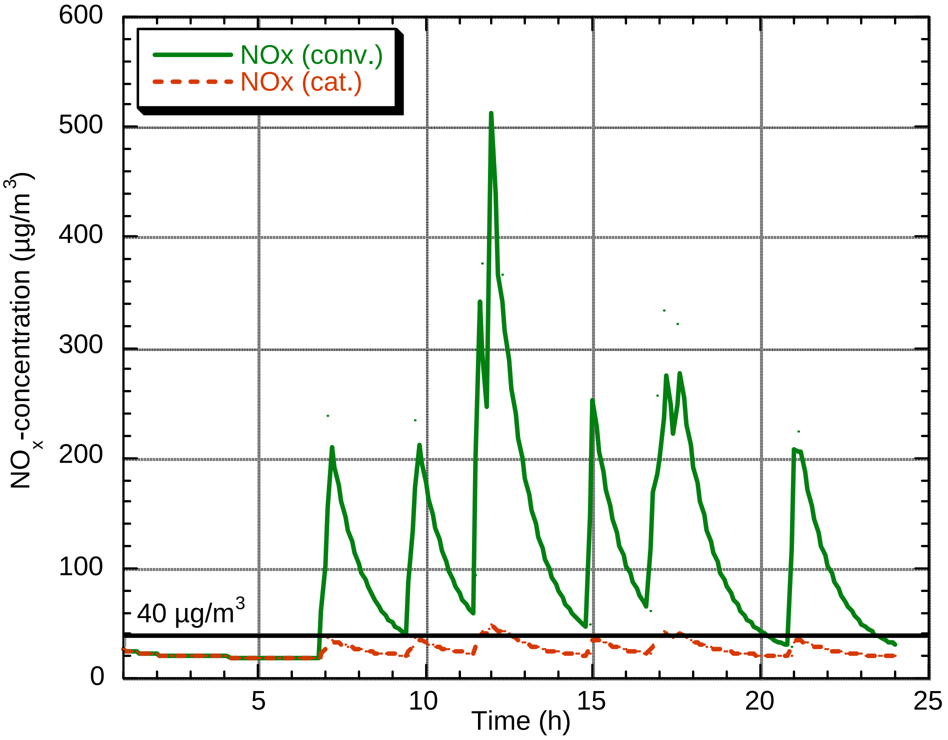


Figure 10 Consequences of catalytic combustion on the NOx-emissions. Outdoor level: 40 µg/m^{3} *(20 ppb).*

The integral NO_x-concentration will change much slower than the momentary NO_x-concentration, as indicated in Figure 11. For the conventional case, the NO_x-concentration will build up to levels about 2 – 2.5 higher than the outdoor concentration during the course of the day. For the catalytic case, the indoor integral NO_x-concentration is always below the outdoor concentration. Consequently, the indoor exposure to NO_x is lower than the outdoor exposure and no additional health risks are probable.

Additional benefits of replacing conventional gas stove burners with catalytic burners are associated to an increased thermal efficiency, as indicated in the introductory experiments. It is also possible to reduce the CO-emissions further by optimising the burner/catalyst-design.

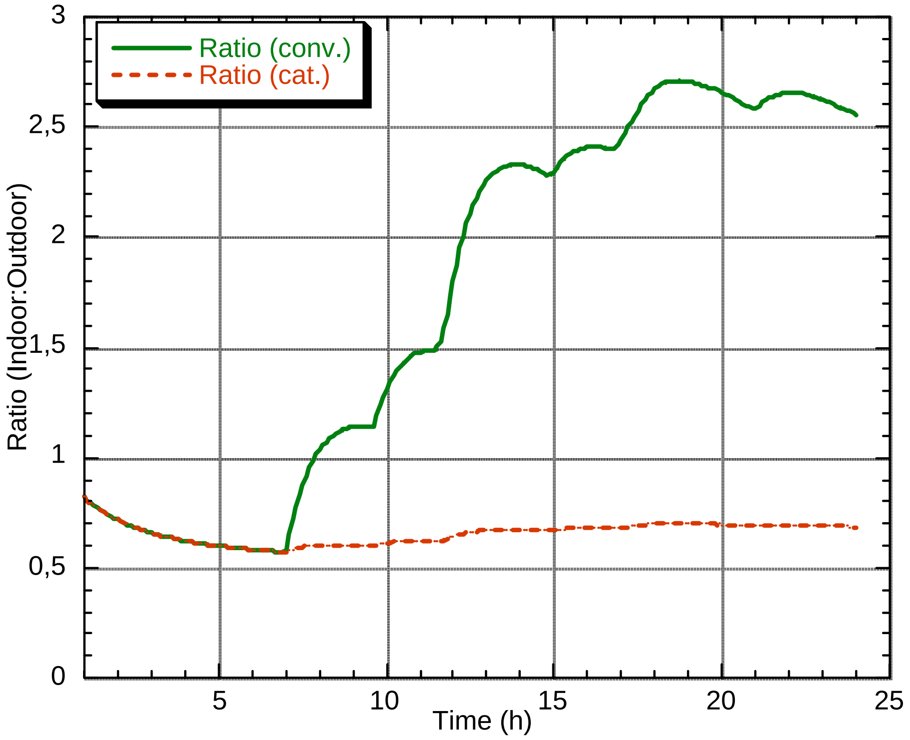


Figure 11 *NO_x-ratio indoor:outdoor, comparison between conventional and catalytic combustion. The graph is based on calculations according to Table 1with different source strengths.*

The combustion characteristics (CO-reduction) can be improved further by increasing the primary aeration. Decreasing the ratio between the area of the nozzle and the area of the flame ports will increase the primary aeration (see Figure 12). Figure 12 is valid for natural gas in conventional atmospheric burners [16]. Increasing the primary aeration is simply accomplished by increasing the flame port area, e.g. by replacing the standard hole-plate with a wire-mesh structure.

Figure 12 also indicates the possible flame port load at a pressure of 100 Pa. The flame port load decreases, as expected, with the degree of aeration.

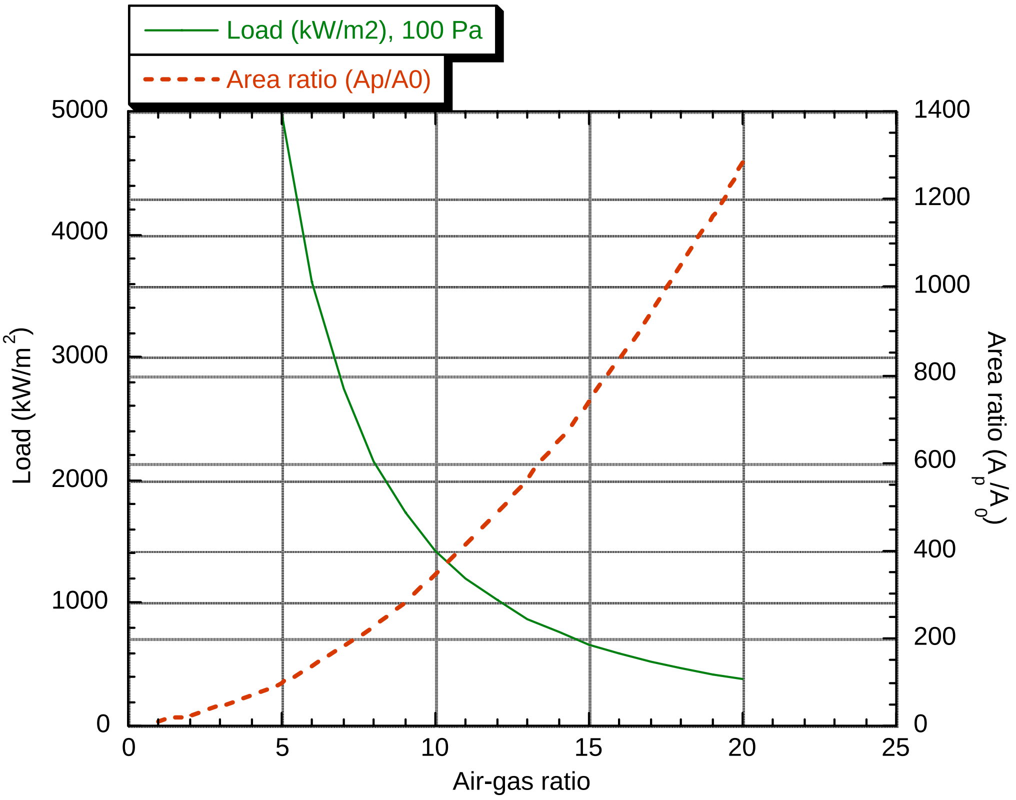


Figure 12 Air-gas ratio in atmospheric burners as a function of the ratio between the flame port area (A_p) and the nozzle area (A_0).

10. Conclusions and continued work

The introductory experiments show that catalytic combustion is easily realised in existing atmospheric burners in gas stoves. The design modifications are very modest and the amount of combustion catalyst is small, which makes the design modification cheap. Indeed, the catalyst cost is estimated to be between 5 and 25 SEK per cooking plate, i.e. less than 100 SEK for a gas stove with four cooking plates.

The emission mapping indicates amazingly low emissions of NO_x and CO. There is also a tendency that the thermal efficiency of the cooking plates can be improved by replacing conventional flame combustion with catalytic combustion.

Comprehensive studies concerning emissions and thermal efficiencies will be conducted in a following-up study during 2002. The study will focus on simple, durable and cheap design alternatives and will cover optimisation and long-term evaluations. Efforts will also be directed towards accurate investigations concerning catalyst deactivation, e.g. spill of food on to the catalyst etc.

The overarching conclusion is that a successful implementation of catalytic combustion in gas stoves finally and permanently should remove the issue concerning health effects caused by indoor use of gas stoves from the agenda. No detrimental health effects are possible when the source strength of NO_2 is reduced by 95% or more. Under these circumstances the indoor concentration of NO_2 will always be below the outdoor concentration.

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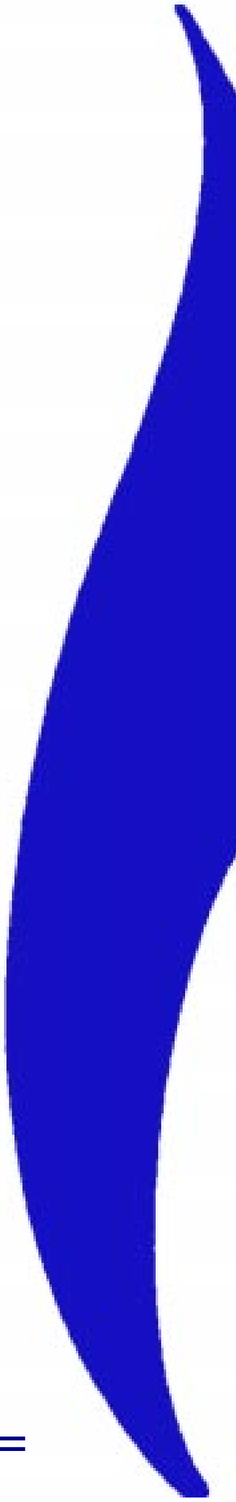

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