INDOOR ENVIRONMENTAL ASSESSMENT METHOD IN RESIDENTIAL KITCHEN

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Nowadays, energy consumption, environmental protection and safety are fundamental issues in design process. In order to reduce energy consumption, buildings become increasingly insulated and air tight. It has controversial effect on indoor environment, therefore, it has become essential to apply an effective ventilation system. This requires detailed design, especially if there is a strong, local source in the space. In residential buildings, gas stoves are significant source of gaseous pollutants and heat load.

Indoor environmental assessments have been carried out in order to evaluate the key parameters. The aim of this studies is to develop a new design and monitoring method of residential kitchens with gas stoves. Primary results of laboratory researches indicate that the largest stovetop burner with power of 2,8kW, has the main role. Significant emissions of nitrogen-oxides have been measured; in an average size kitchen (V_{room}=36m^3) the Hungarian standard NO_X concentration level (200µg/m^3) can be ensured with an exhaust airflow of 1102 m^3/h.

With respect of thermal environmental parameters, heat loads of residential gas stoves could be characterized with convective heat transfer coefficient of 4.5 W/m^{2}K and radiant heat transfer coefficient of 5.9 W/m^{2}K. As regards thermal comfort parameters, PMV index in proved to be applicable in residential kitchens (-0.3 ÷ +2.0). However draught rating cannot be applied, with respect to the temperature limitations.

Key words*: indoor air quality, IAQ, thermal comfort, residential kitchen, gas stove*

1. Introduction

Nowadays there is an increased need for dwellings equipped with energy efficient and save household appliances. According the survey of the Hungarian Central Statistical Office, there are approximately 3, 8 million dwellings in Hungary. To provide healthy, safe and acceptable indoor environment in these buildings, usually ventilation (natural or mechanical) should be applied. Residential kitchen spaces usually represent potential sources of pollutants, especially the one with use of gas stoves. It could be a special challenge to ensure indoor air quality (IAQ) and thermal comfort, because of the significant emission of gaseous pollutants and heat load. Special attention should be paid to the ratio of radiation, as it cannot be removed from the space even by using the most efficient ventilation system [1]. The Hungarian market research data (Panorama of Market Position of Household Appliances, 2005) show that 35% of the purchased items is cooking appliances. Gas stoves are very popular due to the lower prime cost and the reduced operating cost (53% of the Hungarian homes are equipped with them). According the European classification PD CEN/TR 1749:2005, household gas stoves belong to class “A”; combustion products are directly released into the kitchen space. Without mechanical ventilation, the gaseous pollutants: carbon-dioxide (CO_2), nitrogen oxides (NO_x) and - by increased level of CO_2 concentration -, carbon monoxide (CO) will spoil the IAQ and increase health risk.

Increasing CO_2 concentration affect the respiratory centre, NO_x causes respiratory diseases as well, it could cause mucous membrane inflammation in the respiratory tracts, and conjunctivitis. Children and people with asthma are hypersensitive to effects of NO_x [2].

Hungarian comfort related standards and regulations (MSZ EN ISO 7730:2006, MSZ EN 15251:2007) do not specify data for complex indoor environmental design of residential kitchens. Type and concept of ventilation is generally determined since required amount of combustion air with special attention to safety. However, IAQ issues are drawing increasing attention, still there is a need to highlight thermal comfort aspects as well.

In order to help HVAC designers, residential gas stoves need to be characterized with regards to indoor environmental quality aspects. This task requires a general, ready-to-cook stove model, including the determination of key input data. To evaluation of the expected effects, it is essential to define the critical parameters of IAQ and thermal comfort.

The aim of this study is to provide a practical model of a residential gas stove, to enhance design method, and to recommend new ventilation criteria in residential kitchens. However, many studies have been made in order to describe the effects of domestic gas stoves [3,4], these are based on given cooking procedures. Indoor environmental investigations, including laboratory and field studies, CFD simulations, in free-running state have not been carried out yet. With a help of a free-running gas stove model it will be possible to evaluate the indoor environment and the health risk under any circumstances.

2. Methods

The methodology is based on a complex analysis of thermal environment and IAQ. Investigation process could be divided into two major part: objective evaluations and numerical simulations. Objective evaluations include laboratory and field studies, additional calculations and preliminary conclusions. In the course of the numerical simulations different scenarios have been developed by CFD program FLOVENT [5].

This paper is focusing on objective evaluation.

2.1. Fundamental approaches and considerations

Air quality parameters and thermal environment were evaluated under free-running working conditions, regardless of cooking habits or food culture. Three basic cases were carried out, measuring in detail thermal and IAQ parameters: 1.) using the largest burner only, 2.) using the smallest burner only and 3.) using the oven only. In order to determinate the source strength, measurements were performed without any ventilation, so the contaminated air could flow only through the building components or envelope. To describe this situation, air leakage rate was measured by CO_2 tracer-gas method [6], following standard EN ISO 12569:2018.

Investigations were carried out using mechanical ventilation provided by a kitchen exhaust unit as well. No additional ventilation system or exhaust device were applied. Furthermore, there were no additional heat, moisture or pollutant source in the space.

Measurement instruments and sensors are listed in Table 1.

Table 1. Instruments and sensors

Indoor air quality	CO_2 concentration	HORIBA VIA-510 CO_2
	NO,NO_2 and NO_x conc.	HORIBA APNA-360 NO_x
Climatic conditions	outdoor air temperature	TESTO data loggers
	outdoor relative humidity	
Indoor thermal environment	dry air temperature	TESTO 454 / WBGT sensor (DIN 33403, ISO 7243); d=0,15m; ε=0,95
	wet-bulb temperature	
	black globe temperature	
	air velocity	TESTO 454 / Thermal Comfort Probe (EN 13779)

IAQ was evaluated based on average concentration level of the different pollutants. Air samples were taken in three points; perfect mixing was helped by a fan. Thermal comfort monitoring point was placed in front of the stove at a distance x=20cm and at a high h=1,5m. This monitor point was determined according to the expected maximal exposure [1,7].

2.2. Numerical evaluation

2.2.1 Pollutant emission

To evaluate the emission of the stove, the source strength (S) should be calculated. Mathematical model of constant emission [8] is based on the monitoring of the concentration levels at a given time (τ) and provide source strength by Equation (1):

$$S=\left[\left(c_\tau-c_{\tau=0}\right)n_{leak}V_{room}\right] / \left(1-e^{-n_{leak}\tau}\right) \quad (1)$$

Where:
S - is the source strength [mg/m^3; µg/m^3],
$c_\tau-c_{\tau=0}$ - is the level of concentration at a given time [ppm],
τ - is the time [min],
n_{leak} – is the air leakage rate [h^{-1}]
V_{room} – is the effective air volume of the enclosure [m^3].

2.2.2 Thermal comfort parameters

2.2.2.1 Predicted mean vote

Generally, PMV (predicted mean vote) index is used to describe the indoor thermal comfort in residential buildings [8,9]. Although, kitchens should be considered as unique space, due to the significant effects of the stove as a local source. Since former studies showed that this index is not an adequate indicator when it comes to in industrial spaces [7], applicability of the PMV in residential kitchens needs to be examined according to the standard EN ISO 7730:2006. Based on measurement results, partial water pressure, mean radiant temperature, the convective heat transfer coefficient and the surface temperature of clothing need to be previously determined in order to calculate PMV. Therefore, the following calculation methods can be applied.

1. Partial water pressure can be determined since measured dry and wet air temperature according the fundamental psychrometric relations.
2. Mean radiant temperature can be determined based on the black globe temperature and indoor air temperature measurements. However, calculation methods depend on the mode of heat transfer which can be either free (natural) or forced. Mean air velocity of 0.1m/s can be defined as upper

limit for unforced convection. Calculation method for natural convection is given by Equation (2).

$$t_{mrd} = \left[(t_g + 273)^4 + \frac{0,25 \cdot 10^8}{\varepsilon} \left(\frac{|t_g - t_{in}|}{d} \right)^{0,25} |t_g - t_{in}| \right]^{0,25} - 273 \qquad (2)$$

For forced convection mean radiant temperature can be expressed by Equation (3).

$$t_{mrd} = \left[(t_g + 273)^4 + \frac{1,1 \cdot 10^8 v^{0,6}}{\varepsilon\, d^{0,4}} |t_g - t_{in}| \right]^{0,25} - 273 \qquad (3)$$

Where:
t_{mrd} – is the mean radiant temperature [°C],
t_g – is the black globe temperature [°C],
t_{in} – is the dry indoor air temperature [°C],
ε – is the emissivity of the globe [-],
d – is the diameter of the globe [m].

For the standard black globe (EN ISO 7726:2003), values of ε=0,95 and d=0,15m can be used [10].

3. The convective heat transfer coefficient also depends on type of convection. Calculation method is given by Equation (4) for natural convection and by Equation (5) [8].

$$\alpha_c = 2,38(t_{clo} - t_{in})^{0,25} \qquad (4)$$

$$\alpha_c = 12,2\ v^{0,5} \qquad (5)$$

Where:
α_c – is the convective heat transfer coefficient [W/m^{2}K]
t_{clo} – is the surface temperature of clothing [°C],
v – is the mean air velocity [m/s]
t_{in} – is the dry indoor air temperature [°C].

4. The surface temperature of clothing is given as a complex function of personal data and measured thermal parameters, in close conjunction with the PMV theory. The mathematical expression of surface temperature of clothing can only be solved by an iterative process [8].

2.2.2.2 Turbulence intensity

[deleted sentences] According to the standard EN ISO 7730:2006, draught rating can be calculated based on air temperature, mean air velocity and the turbulence intensity. Validity of the model need to be checked according to the given limitations.

2.2.2.3 Radiant heat transfer coefficient

Radiant heat transfer coefficient can be approximated by Equation (6), if the indoor temperature stays within a relatively small interval (10-30°C) [10].

$$\alpha_r = 4,6(1 + 0,01\overline{t_{mrd}}) \qquad (6)$$

Where:
α_r – is the radiant heat transfer coefficient [W/m^{2}K]
t_{mrd} – is the mean radiant temperature [°C],

2.2.2.4 Draught rating

Draught rating shall be performed according to EN ISO 7730:2006. The model has been developed to people at light activity, exposed to air temperature interval of 20°C to 26°C, mean air velocity of 0,05 m/s to 0,4 m/s, and turbulence intensity of 0% to 70%.

3. Results

This paper is focusing on laboratory measurements, conducted in the Indoor Air Quality Laboratory (Department of Building Service and Process Engineering), located: Budapest, Hungary. Investigated stove was a brand new, high quality equipment, which could be considered as a popular model in Hungary. During the assessments, the gas stove was the only heat and pollutant source in the kitchen and internal moisture load was equal to zero. Mechanical ventilation was produced by just the exhaust hood unit, and there was no additional fresh air intake.

3.1. Measurement results

3.1.1 Basic input data

Dimensions of the stove were 600x600x850 mm, oven-ventilation openings were placed stovetop in the rear. Oven is equipped with insulated glass. The largest stovetop burner is placed near to the front plate. The wall-mounted hood was positioned at the height of 80cm above the stovetop. The cross-section area of the hood was 600x600mm, ratio of free-sectional area was 0,45. Determined personal parameters are: the level of activity is 1,6met, the thermal resistance of clothing is 0,5clo and the ratio of the surface area of the clothed body to the surface area of the nude body is 1.1.

3.1.2 Preliminary measurements

Fundamental parameters of types of ventilation and characteristic data of the three working conditions are listed in Table 2. (gas type 2H, net calorific value NCV=34190kJ/m^3). Since the measured gas consumption value of the largest burner has the highest value, the impact on indoor environment was expected to be the most significant.

Table 2. Preliminary measurements

Working conditions			
	Burner "B"	Burner "H"	Oven
NGC [m^3/h]	0.30	0.10	0.27
P [kW]	2.8	0.9	2.6
Ventilation parameters			
n_{leak} [1/h]	0.5		
V_{ex} [m^3/h]	180		

Measured power correspond to the catalogue data (3.0 kW for the largest burner, 1.0 kW for Burner “H” and 2.5 kW for the oven).

3.1.3 Evaluation of IAQ

Contaminated IAQ was evaluated by changes of CO_2 and NO_x concentrations. The average initial (τ=0min) indoor CO_2 concentration was 520ppm, NO_x concentration was 71μg/m^3. Figure 1. a) shows the increase of the average CO_2 concentration level in comparison with the initial level if there is no mechanical ventilation. The effects of the kitchen exhaust unit can be seen in Figure 1. b). NO_x concentration changes are presented in Figure 2. a) when exhaust fan is off and b) when the exhaust fan is on.

Visualizations of the results show the significant effect of the largest stovetop burner. Without ventilation, CO_2 increase was 1325ppm, while NO_x concentration rise was 1409μg/m^3 during measurement period of 60 minutes. The effect of the kitchen exhaust unit can be described with the following average values: CO_2 concentration was decreased by 18%, NO_x concentration was decreased by 25%.

Using the oven only, pollutant concentration was similarly high, CO_2 increase was 955ppm, while NO_x concentration rise was 1189 μg/m^3 during measurement period of 60 minutes. The average values to describe the effect of the kitchen exhaust unit were measured: CO_2 concentration was decreased by 50%, and NOx concentration was decreased by 54% thanks to the mechanical ventilation.

No significant effect of the hood was observed during the operation of the smallest stovetop burner.

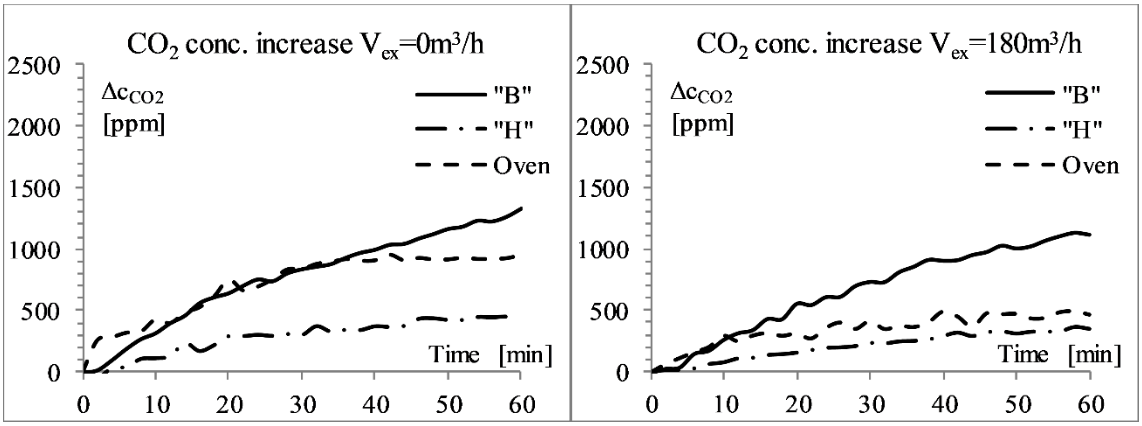

Figure 1.a) CO_2 concentration increase (Δc_{CO2}), when exhaust fan is off and b) CO_2 concentration increase (Δc_{CO2}), when exhaust fan is on

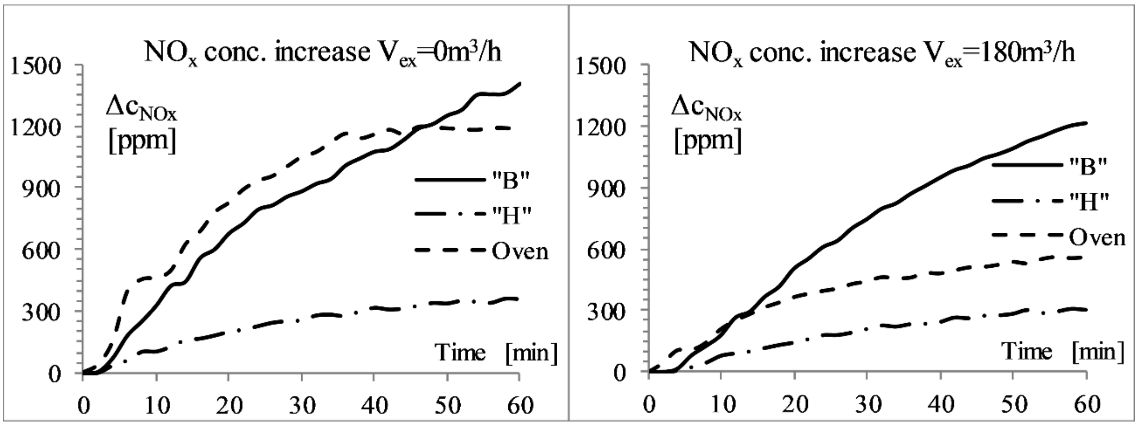

Figure 2.a) NO_x concentration increase (Δc_{NOx}), when exhaust fan is off and b) NO_x concentration increase (Δc_{NOx}), when exhaust fan is on

3.1.4 Monitoring of the thermal parameters

3.1.4.1 Climatic conditions

Outdoor temperature and relative humidity were recorded every 5 minutes. Measurement results show slight changes over time. Minimum, maximum and mean values are summarized in Table 3.

Table 3. Outdoor climatic conditions

		$V_{ex}=0m^3/h$			$V_{ex}=180m^3/h$		
		"B"	"H"	Oven	"B"	"H"	Oven
t_{out}[°C]	min	2,6	2,2	3,1	8,5	14,1	2,1
	max	2,7	2,4	3,5	9,8	14,6	2,2
	mean	2,7	2,3	3,3	9,1	14,3	2,2
	std.dev.	0,03	0,10	0,13	0,44	0,16	0,05
φ_{out}[%]	min	77,6	78,2	64,9	39,3	31,2	78,9
	max	81,1	79,8	66,5	41,8	34,1	80,6
	mean	80,0	78,8	65,7	40,3	32,8	79,5
	std.dev.	0,97	0,46	0,43	0,81	0,87	0,56

Results proved, that due to the structure of the building envelope, changes of the outdoor climatic or air quality circumstances have negligible effects on indoor environment during the measurements.

3.1.4.2 Indoor thermal parameters

Indoor temperature and air velocity data were collected at the monitoring point, representing the effects on the occupant. Temperature data were measured every second minute; results are summarized in Table 4.

Dry air temperature data are presented in Figure 3. a) when exhaust fan is off and b) when exhaust fan is on. Results show the significant effect of the large burner. Dry air temperature increase of 5K was resulted in 60 minutes. Convective part was reduced by using the hood, therefore temperature difference was decreased by 71%. In case of oven, temperature difference was reduced by 27% due to the use of exhaust unit. No significant effect of the hood was observed during the operation of the smallest stovetop burner.

Air velocity results were recorded every millisecond, are listed in Table 5. If there is no ventilation, mean air velocity were determined by the buoyancy forces generated by the heat load. Standard deviation is within the interval of 14-17%, with respect of the mean value, significant differences between the working conditions could not be observed. By using the hood, forced air movement resulted lower level of the standard deviation in case of the stovetop burners (7-8%). However, if the oven was operating, mean air velocity was decreased by 35% at the monitor point, and higher level of standard deviation was calculated (24%).

Table 4. Indoor temperature data when exhaust fan is off or on

		V_{ex}=0m³/h			V_{ex}=180m³/h		
		"B"	"H"	Oven	"B"	"H"	Oven
t_{in}[°C]	min	25,9	27,5	24,3	25,6	23,2	25,6
	max	30,9	29,2	27,4	27,2	25,1	27,9
t_{wet}[°C]	min	15,9	16,6	14,1	15,3	14,3	15,8
	max	19,0	18,1	16,4	17,1	15,7	17,4
t_g[°C]	min	27,3	27,9	24,8	26,2	23,3	26,1
	max	32,1	30,2	28,3	28,2	25,5	28,8

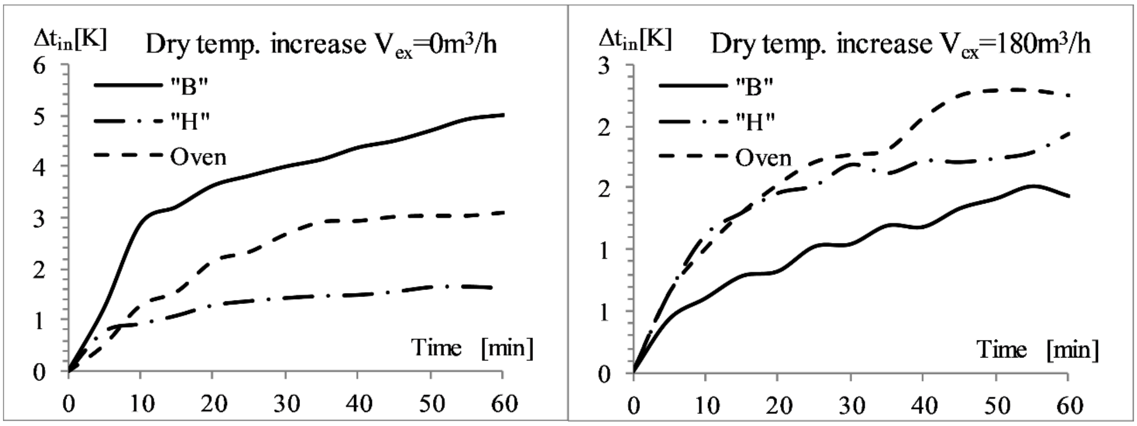

Figure 3. a) Dry air temperature increase when exhaust fan is off and b) when exhaust fan is on

Table 5. Air velocity monitoring during use of different stove parts and different condition (when exhaust fan is on or off)

		V_{ex}=0m³/h			V_{ex}=180m³/h		
		"B"	"H"	Oven	"B"	"H"	Oven
v [m/s]	min	0.088	0.112	0.106	0.105	0.163	0.054
	max	0.162	0.191	0.178	0.132	0.197	0.133
	mean	0.140	0.163	0.152	0.119	0.179	0.098
	std.dev.	0.024	0.026	0.021	0.009	0.014	0.023

3.2. Numerical evaluation

3.2.1 Source strength

Pollutant emission was evaluated by calculating the source strength for CO_2 and NO_x, according Equation (1). Emission data can be seen in Figure 1. and Figure 2., measured air leakage rate is presented in Table 2. Calculated source strength data are summarized in Table 6.

Table 6. Source strength data

	"B"	"H"	Oven
S_{CO2} [mg/h]	370 272	130 565	277 864
S_{NOx} [µg/h]	218 670	61 058	237 306

3.2.2 PMV index

3.2.2.1 Applicability check

For PMV calculation, personal parameters were determined as basic input data (M/A_{Du}=1,6met, η=0, I_{clo}=0,5clo, f_{clo}=1,1) in accordance the limitations of EN ISO 7730:2006. According the standard PMV index can be applied if the given parameters remain the recommended intervals (t_{in}=10-30°C, t_{mrd}=10-40°C, v=0-1m/s, p_w=0-2700Pa). Measured data of dry air temperature (Table 4.) and air velocity (Table 5.) remained between the limits. Calculated mean radiant temperature and the partial water pressure data are summarized in Table 7. As it can be seen, results are within the given interval (60 minutes).

Table 7. Applicability check of PMV when exhaust fan is on or off

		V_{ex}=0m³/h			V_{ex}=180m³/h		
		"B"	"H"	Oven	"B"	"H"	Oven
t_{mrd}[°C]	min	28,0	28,1	25,2	26,5	23,4	26,5
	max	32,9	30,9	29,0	28,8	25,7	29,6
p_w[Pa]	min	1152	1188	948	1061	1046	1137
	max	1447	1366	1156	1292	1169	1306

3.2.2.2 Clothing surface temperature and convective heat transfer coefficient

Convective heat transfer coefficient can be determined according to Equation (4) and (5), depending on the type of convection. Average values of the convective heat transfer coefficient and the calculated clothing surface temperature data are presented in Table 8.

Table 8. Clothing surface temperature and the convective heat transfer coefficient when exhaust fan is on or off

		V_{ex}=0m³/h			V_{ex}=180m³/h		
		"B"	"H"	Oven	"B"	"H"	Oven
t_{clo}[°C]	min	28.0	28.1	25.2	26.5	23.4	26.5
	max	32.9	30.9	29.0	28.8	25.7	29.6
α_c [W/m²K]	mean	4.5	4.9	4.7	4.2	3.6	5.0

3.2.2.3 PMV index

Based on the applicability check, it can be concluded that PMV index is applicable to characterize influence of the residential gas stove on the thermal environment. Changes of the PMV index are presented in Figure 4. a) when the exhaust fan is off and b) when the exhaust fan is on. PMV index was increased in accordance with the rising indoor temperature from -0,3 to +2,0. The results refer also the leading role of the largest burner. As it was expected, change of the PMV was decreased by removing the convective heat load. Therefore, results refer to that convective heat load is dominant with respect of thermal comfort.

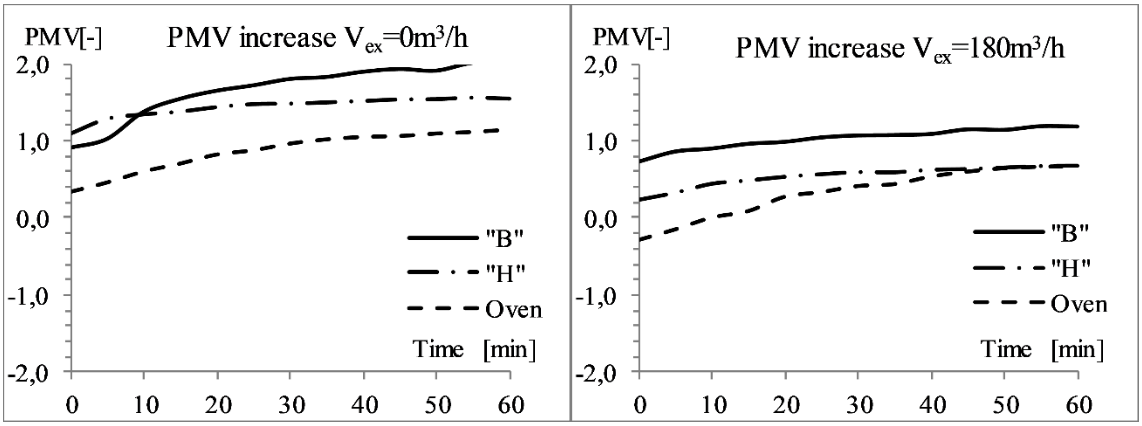

Figure 4. a) Change of the PMV index when exhaust fan is off and b) when exhaust fan is on

3.2.3 Radiant heat transfer coefficient

Measured indoor temperature (see Table 4.) ranged within the recommended values, therefore radiant heat transfer coefficient can be calculated with Equation (8). Obviously, radiant heat transfer coefficient will increase with the change of mean radiant temperature. According the results are listed in Table 9., this change proved to be slight, therefore an overall mean value of 5.9 W/m^{2}K. This value can be applied to characterize radiant heat transfer generated by domestic gas stoves.

Table 1. Radiant heat transfer coefficient when exhaust fan is on or off

		V_{ex}=0m^3/h			V_{ex}=180m^3/h		
		"B"	"H"	Oven	"B"	"H"	Oven
α_r [W/m^{2}K]	min	5.9	5.9	5.8	5.8	5.7	5.8
	max	6.1	6.0	5.9	5.9	5.8	6.0
	mean	6.0	6.0	5.9	5.9	5.7	5.9
	std.dev	0.077	0.036	0.063	0.032	0.033	0.047

3.2.4 Turbulence intensity

Turbulence intensity should be calculated using Equation (7), based on air velocity monitoring data are listed in Table 5. Calculated turbulence intensity data are presented in Table 10.

Table 10. Turbulence intensity when exhaust fan is on or off

		V_{ex}=0m³/h			V_{ex}=180m³/h		
		"B"	"H"	Oven	"B"	"H"	Oven
Tu [%]	min	41,3	44,3	25,3	27,4	37,5	36,5
	max	67,1	66,2	35,8	40,0	52,7	76,0
	mean	52,1	51,1	30,7	32,7	43,5	50,0
	std.dev.	8,5	8,6	3,4	4,0	5,1	13,6

According to Table 4. Dry air temperature is over the given interval in most of the cases (except at the smallest burner with ventilation), therefore draught rate DR cannot be applied in this study.

4. Conclusions

According to the results, domestic gas stoves shall be considered as sources of significant amount of CO_2 and NO_x, and heat load. Despite popularity of the gas stoves, there are no standard values or methods to perform a complex indoor environmental analysis in residential kitchens in Hungary. To provide basic data and general design assumptions, a comprehensive research has been carried out, including laboratory assessments, field studies and numerical simulations. First results of laboratory studies have indicated the major effect of gas stoves on indoor environment. However, priority should be given to contaminated or poor IAQ, and therefore thermal issues must be taken into consideration. Product of combustion will increase the level of gaseous pollutants; therefore, the amount of gas consumption should indicate the level of pollutants. Based on the gas input, importance of the largest stovetop burner and the oven is similarly high, effect of the smallest burner is more limited. It should be highlighted, that position of the burner has significant influence on the indoor environment at the monitor point. Effect of different source localizations need further investigations. Calculating the source strength data, results can be compared to the Hungarian IAQ standards and recommendations (MSZ 04.125/1-1982 and 14/2001.(V.9.) KöM-EüM-FVM). Figure 5. can be useful tools to determinate the required minimal air exchange rate as a function of the volume of the room (V_{room} [m³]).

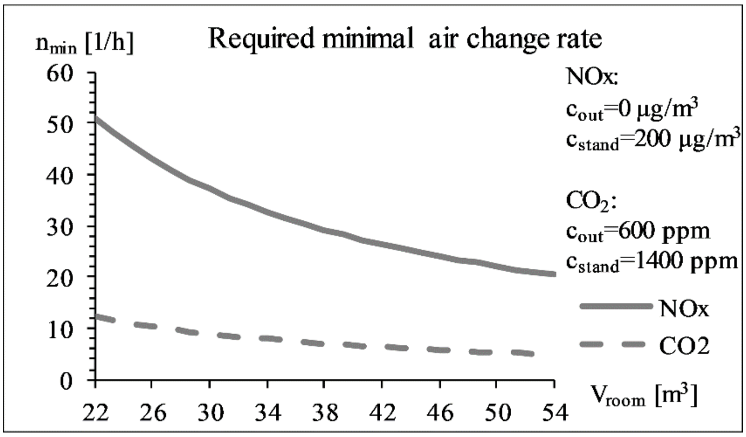

Figure 1. Required minimal air exchange rate

In an average size kitchen (V_{room}=36m³), it requires $V_{ex,CO2}$=266m³/h and $V_{ex,NOx}$=1102 m³/h ventilation to meet the Hungarian standards MSZ 04.125/1-1982 and 14/2001.(V.9.) KöM-EüM-FVM. Recommended level of NO_x concentration cannot be ensured by using an average local exhaust unit with V_{ex}=180m^3/h. At this level of ventilation indoor air pollution can be reduced by 57% in case of the oven, and by 17% if the largest burner is used. However, effect of the noise generated by the hood requires further analysis. Investigation of the thermal environment leads to that PMV index is applicable to describe the effects of the residential gas stove. According to the standard EN ISO 7730:2006, all the key parameters stayed within the permitted interval during the measuring period of 60min. Significant effect of the largest stovetop burner can be also detected by analysing the thermal parameters. During the operation of the largest burner, kitchens exhaust unit reduced the dry temperature by 71%, and this resulted in 60% decrease of the PMV. This indicates the major role of convective heat load. Convective heat transfer coefficient is determined by the type of convection. Air velocity monitoring showed the strong influence of buoyancy forces. Based on the indoor temperature results, radiant heat transfer coefficient data can be calculated with a simplified method. To evaluate thermal environment around domestic gas stoves, convective heat transfer coefficient of 4,5 W/m^{2}K and radiant heat transfer coefficient of 5.9 W/m^{2}K could be taken into consideration as specific values. Draught rating according to EN ISO 7730:2006 cannot be applicable due to the relatively high air temperature.

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