CFD Modelling of Indoor Air Quality and Thermal Comfort

LÁSZLÓ KAJTÁR – ANITA LEITNER
Department of Building Service Engineering
Budapest University of Technology and Economics
H-1111 Budapest, Műegyetem rkp. 9
HUNGARY

Abstract: Gaseous emission - CO_2, NO, and NO_x of gas stove has significant and harmful effect on indoor air quality (IAQ) in residential kitchens. To avoid increasing health risk it is essential to use mechanical ventilation such as kitchen hood. However, according former laboratory studies, exhaust air flow generated by typical hoods is not adequate to achieve required IAQ.
In order to describe required ventilation of kitchens, emission of gas stoves has been investigated for years at Department of Building Service Engineering, BUTE. Laboratory and field studies were carried out, afterwards, based on the results, pollutant distribution was described by CFD simulation (FLOVENT).
In this paper an overview of method and results of CFD modelling is published.

Key-words: IAQ, CFD modelling, kitchen ventilation, CO_2, NO_x,

1 Introduction

Gaseous emission - CO_2, NO, and NO_x of gas stove has significant and harmful effect on indoor air quality (IAQ) in residential kitchens. Former laboratory studies have shown that to provide adequate indoor air quality significant higher supply airflow is required than to ensure burning process [2]. Considering the complexity of describing equations CFD model should be used to predict indoor air quality and concentration distribution. Based on results of computational investigations required supply airflow can be estimated with respect of IAQ requirements.

2 Methods

Model presented in this paper can be applied in the following case:

- Mechanical ventilation is provided by kitchen exhaust ventilation, installed above the stove. Room air recirculation is not feasible.
- Gaseous emission of stove consists of carbon dioxide, nitric oxide and nitrogen dioxide.

Using the model concentration distribution in the kitchen can be predicted and required ventilation can be estimated.

Concentration distribution can be predicted based pollutant emission and applied ventilation system.

Chemical pollution loads (CO_2, NO, NO_2) of stoves have been measured in IAQ laboratory of Department of Building Service Engineering, BUTE. As measuring loads, mechanical ventilation did not operate, air exchange was provided only by natural filtration. To carry on further calculation filtration exchange rate had been measured beforehand [3].

2.1 Describing equations

Results of CFD models are based on solutions of Navier-Stokes equations, the energy equation, the mass and concentration equations as well as the transport equations for turbulent velocity and its scale [4].

2.1.1 Conservation of mass

In case of turbulent flow, velocity can be estimated as a sum of a time-mean and a fluctuating component:

$$u = \overline{u} + u'; \quad v = \overline{v} + v'; \quad w = \overline{w} + w'; \qquad (1)$$

Considering in $\delta\tau$ time interval $u \approx \overline{u}$; $v \approx \overline{v}$; $w \approx \overline{w}$; equation (1) become:

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial}{\partial x}(\rho \cdot u) + \frac{\partial}{\partial x}(\rho \cdot v) + \frac{\partial}{\partial x}(\rho \cdot w) = 0 \qquad (2)$$

2.1.2 Navier-Stokes equation

Static pressure can be described as a sum of a time-mean and a fluctuating component as well ($p = \overline{p} + p'$). Considering x, y and z coordinates, following equations are:

x direction:

$$\frac{\partial}{\partial \tau}(\rho \cdot \overline{u}) + \frac{\partial}{\partial x}(\rho \cdot \overline{u}^2) + \frac{\partial}{\partial y}(\rho \cdot \overline{u} \cdot \overline{v}) + \frac{\partial}{\partial z}(\rho \cdot \overline{u} \cdot \overline{w}) =$$
$$= -\frac{\partial \overline{p}}{\partial x} + \frac{\partial}{\partial x}\left(\mu \frac{\partial \overline{u}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial \overline{u}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial \overline{u}}{\partial z}\right) +$$
$$+ \frac{1}{3}\frac{\partial}{\partial x}\mu\left(\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} + \frac{\partial \overline{w}}{\partial z}\right) +$$
$$+ \frac{\partial}{\partial x}\left(-\rho \cdot \overline{u'^2}\right) + \frac{\partial}{\partial y}\left(-\rho \cdot \overline{u' \cdot v'}\right) + \frac{\partial}{\partial z}\left(-\rho \cdot \overline{u' \cdot w'}\right) + \rho \cdot g_x \tag{3}$$

y direction:

$$\frac{\partial}{\partial \tau}(\rho \cdot \overline{v}) + \frac{\partial}{\partial x}(\rho \cdot \overline{u} \cdot \overline{v}) + \frac{\partial}{\partial y}(\rho \cdot \overline{v}^2) + \frac{\partial}{\partial z}(\rho \cdot \overline{v} \cdot \overline{w}) =$$
$$= -\frac{\partial \overline{p}}{\partial y} + \frac{\partial}{\partial x}\left(\mu \frac{\partial \overline{v}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial \overline{v}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial \overline{v}}{\partial z}\right) +$$
$$+ \frac{1}{3}\frac{\partial}{\partial y}\mu\left(\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} + \frac{\partial \overline{w}}{\partial z}\right) +$$
$$+ \frac{\partial}{\partial x}\left(-\rho \cdot \overline{u' \cdot v'}\right) + \frac{\partial}{\partial y}\left(-\rho \cdot \overline{v'^2}\right) + \frac{\partial}{\partial z}\left(-\rho \cdot \overline{v' \cdot w'}\right) + \rho \cdot g_y$$

z direction:

$$\frac{\partial}{\partial \tau}(\rho \cdot \overline{w}) + \frac{\partial}{\partial x}(\rho \cdot \overline{u} \cdot \overline{w}) + \frac{\partial}{\partial y}(\rho \cdot \overline{v} \cdot \overline{w}) + \frac{\partial}{\partial z}(\rho \cdot \overline{w}^2) =$$
$$= -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left(\mu \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial w}{\partial z}\right) +$$
$$+ \frac{1}{3}\frac{\partial}{\partial z}\mu\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) +$$
$$+ \frac{\partial}{\partial x}\left(-\rho \cdot \overline{u' \cdot w'}\right) + \frac{\partial}{\partial y}\left(-\rho \cdot \overline{v' \cdot w'}\right) + \frac{\partial}{\partial z}\left(-\rho \cdot \overline{w'^2}\right) + \rho \cdot g_z \tag{5}$$

The terms used describe velocity fluctuation in equations (3) (4) and (5) are the Reynolds stress indexes (time-mean value of velocity fluctuation). To determinate Reynolds stresses proper turbulence model should be used. Considering isentropic ($\overline{u'^2} = \overline{v'^2} = \overline{w'^2}$) flow Reynolds stresses can be calculated based on turbulence viscosity:

$$-\rho \cdot \overline{u'^2} = 2 \cdot \mu_t \frac{\partial \overline{u}}{\partial x} - \frac{2}{3}\rho \cdot k$$
$$-\rho \cdot \overline{v'^2} = 2 \cdot \mu_t \frac{\partial \overline{v}}{\partial y} - \frac{2}{3}\rho \cdot k$$
$$-\rho \cdot \overline{w'^2} = 2 \cdot \mu_t \frac{\partial \overline{w}}{\partial z} - \frac{2}{3}\rho \cdot k \tag{6}$$

$$-\rho \cdot \overline{u' \cdot v'} = \mu_t\left(\frac{\partial \overline{u}}{\partial y} + \frac{\partial \overline{v}}{\partial x}\right)$$
$$-\rho \cdot \overline{v' \cdot w'} = \mu_t\left(\frac{\partial \overline{v}}{\partial z} + \frac{\partial \overline{w}}{\partial y}\right)$$
$$-\rho \cdot \overline{u' \cdot w'} = \mu_t\left(\frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w}}{\partial x}\right) \tag{7}$$

where k is the kinetic energy of the turbulent velocities:

$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \tag{8}$$

Based on k-ε turbulence viscosity model:

$$\mu_t = C_\mu \cdot \rho \cdot \frac{k^2}{\varepsilon} \quad (4) \tag{9}$$

where C_μ (=0.09) is an empirical constant, moreover ε is the dissipation rate of mean turbulent viscosity.

2.1.3 Conservation of thermal energy

The conservation of thermal energy in the control volume is:

$$\frac{\partial}{\partial \tau}(\rho \cdot t) + \frac{\partial}{\partial x}(\rho \cdot u \cdot t) + \frac{\partial}{\partial y}(\rho \cdot v \cdot t) + \frac{\partial}{\partial z}(\rho \cdot w \cdot t) =$$
$$= \frac{\partial}{\partial x}\left(\Gamma \frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma \frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\Gamma \frac{\partial t}{\partial z}\right) \tag{10}$$

where $\Gamma = \frac{\mu}{\sigma}$; and parameter σ is depend on Prandtl and Schmidt numbers.

2.1.4 Conservation of mass

In equation represent conservation of mass $\dot{G}$ is the chemical load (for investigated pollutant):

$$\frac{\partial}{\partial \tau}(\rho \cdot c)+\frac{\partial}{\partial x}(\rho \cdot u \cdot c)+\frac{\partial}{\partial y}(\rho \cdot v \cdot c)+\frac{\partial}{\partial z}(\rho \cdot w \cdot c)=$$
$$=\frac{\partial}{\partial x}\left(\Gamma \frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma \frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma \frac{\partial k}{\partial z}\right)+$$
$$+\frac{\partial}{\partial x}\left(-\rho \cdot \overline{u' \cdot c'}\right)+\frac{\partial}{\partial y}\left(-\rho \cdot \overline{y' \cdot c'}\right)+\frac{\partial}{\partial z}\left(-\rho \cdot \overline{w' \cdot c'}\right)+\dot{G}$$

(11) (14)

Defining the investigated phenomenon further condition should be given to describe e.g.: initial circumstances.

Initial and definite conditions:

$$t_{sfi}\big|_{i=1..4}(\tau=0)=t_{indoor}=20°C$$
$$\dot{G}=0$$
$$c(0,x,y,z)=c_0$$
$$c_{outdoor}=0=\text{constant}$$
$$t_{supply}=\text{constant}$$
$$\dot{V}_{fil}=\text{constant}$$
$$\dot{V}_{supply}(\tau=0)=0=\text{constant}$$

(12)

Boundary conditions:

$$t_{sfi}\big|_{i=1..4}=f_i\big|_{i=1..4}(\tau,x,y,z)\big|_{\tau\le 90}$$
$$\int_A \alpha * \left[t_{sfi}(\tau)-t_{indoor}(\tau)\right]\cdot dA=\int_V c\cdot\rho\cdot\Theta\cdot dV+$$
$$+c\cdot\rho\cdot\Theta\cdot\dot{V}\cdot d\tau$$
$$\Theta(\tau,x,y,z)\big|_{x\ge 0;y\ge 0}=t(\tau,x,y,z)-t_{indoor}$$

(13)

3 CFD model

To estimate required exhaust air flow CFD modelling has been made by FLOVENT. Number of cases has been investigated as regards amount of air removed by kitchen hood. Supply air has been provided using air terminal devices installed above the windows. Validity of CFD model has been investigated based on results of former laboratory and filed studies.

3.1 Modelling considerations

Geometrical model has developed according architectural parameters of enclosure investigated at field studies. Gas stove model (P=5kW) has been made following proportions of a device with average technical parameters, therefore commonly used one. Pollution loads have been estimated by laboratory measurements.

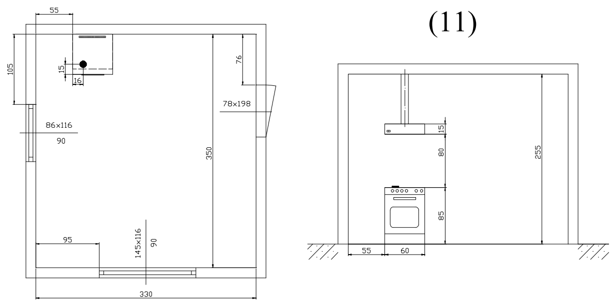

Figure 1. Plan of model kitchen (V_{room} = 29,5 m^3)

Burner power P=5kW		
Air flow extracted by hood (h =80 cm)	Supply air terminal device	Pollution load
0 m^3/h	-	(15) G_{CO2}= 1,80*10^{-4} kg/s G_{NO2}= 2,48*10^{-8} kg/s G_{NO} = 7,80*10^{-8} kg/s
60 m^3/h	1 x 60 m^3/h	
180 m^3/h	2 x 90 m^3/h	
250 m^3/h	2 x 125 m^3/h	
500 m^3/h	4 x 125 m^3/h	

Table 1. Investigated kitchen ventilation systems

Thermal properties of stove have been studied by measuring air temperature and air velocity around the working stove at 10 points and surface temperature. To describe effect of increasing surface temperature approximate functions have been developed based on measurements' results.

To describe time depending parameters time-step(s) has to be estimated. Total transient period (60min) has been divided into following steps: 2min, 5min, 10min, 15min, 20min, 30min, 45min and 60min. Data saved at 10th, 30th and 60th minutes.

To model kitchen hood fixed flow element has been used in size 60 x 52 cm, with 45% free area ratio. Supply air terminal units have been described in a similar way. Each diffuser (4 x 50cm, with 50% free area ratio) is placed above the windows (no more than two for one window).
Exhaust and supply airflows in every investigated situations see in Table 1.

4 Results

In following Figures results from a selected plane are presented. Considering expected position of occupants, parameters have been followed at 10 monitor points placed in front of the stave, at 1.5m high along the centreline of the burner, in every 10cm.

Hereby concentration (CO_2, NO, NO_2) distribution, indoor air temperature and mean air velocity are published at $\dot{V}_{ex}$ =0 and at $\dot{V}_{ex}$ =180 m^3/h airflow in 30minutes after turn on the stove (mechanical ventilation start at same time).

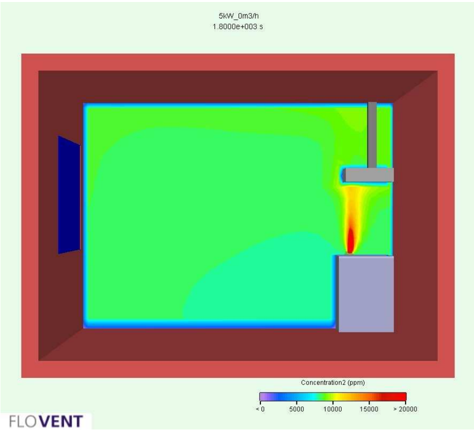

Figure 2. CO_2 concentration
(τ=30min, V_{ex}=0 m^3/h); Kajtár-Leitner (2006)

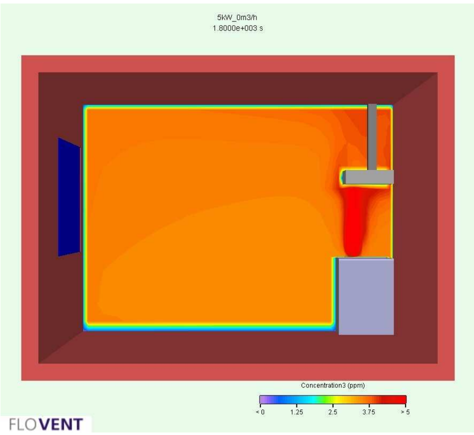

Figure 3. NO concentration
(τ=30min, $\dot{V}_{ex}$ =0 m^3/h); Kajtár-Leitner (2006)

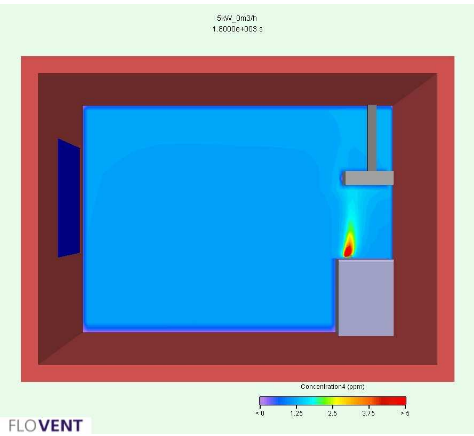

Figure 4. NO_2 concentration
(τ=30min, $\dot{V}_{ex}$ =0 m^3/h) Kajtár-Leitner (2006)

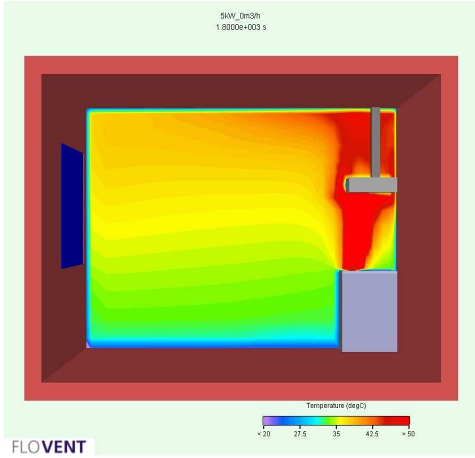

Figure 5. Indoor air temperature
(τ=30min, $\dot{V}_{ex}$ =0 m^3/h); Kajtár-Leitner (2006)

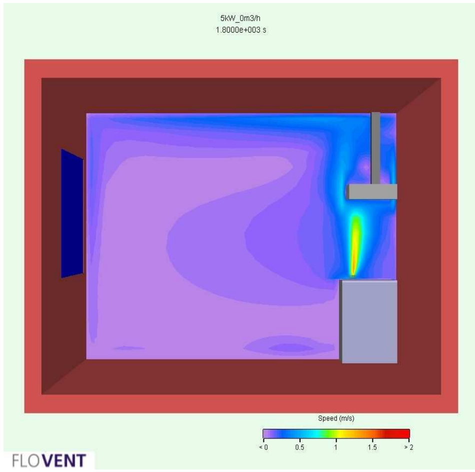

Figure 6. Indoor air temperature
(τ=30min, $\dot{V}_{ex}$ =0 m^3/h); Kajtár-Leitner (2006)

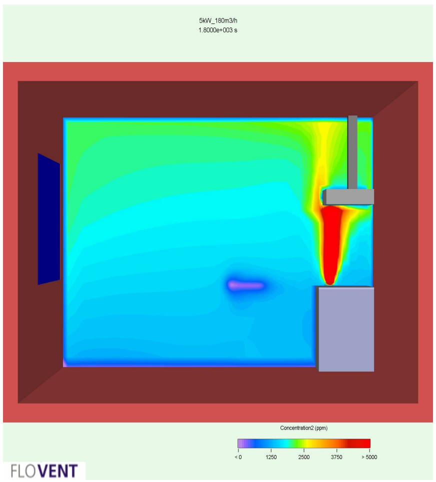

Figure 7. CO_2 concentration
(τ=30min, $\dot{V}_{ex}$ =180 m^3/h); Kajtár-Leitner (2006)

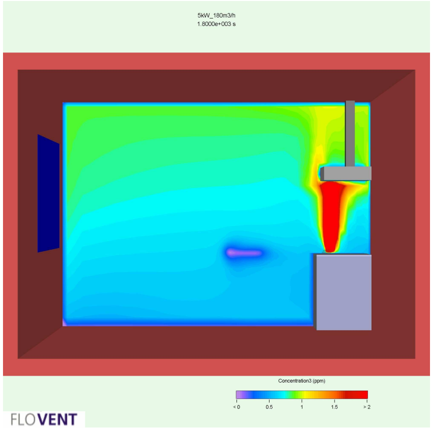

Figure 8. NO concentration
(τ=30min, $\dot{V}_{ex}$ =180 m^3/h); Kajtár-Leitner (2006)

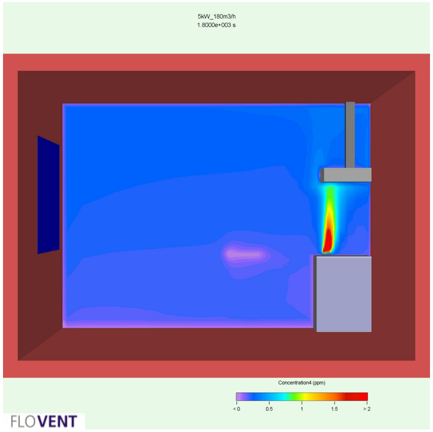

Figure 9. NO_2 concentration
(τ=30min, $\dot{V}_{ex}$ =180 m^3/h) Kajtár-Leitner (2006)

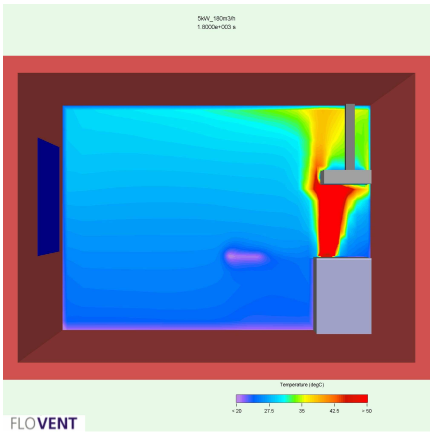

Figure 10. Indoor air temperature
(τ=30min, $\dot{V}_{ex}$ =180 m^3/h); Kajtár-Leitner (2006)

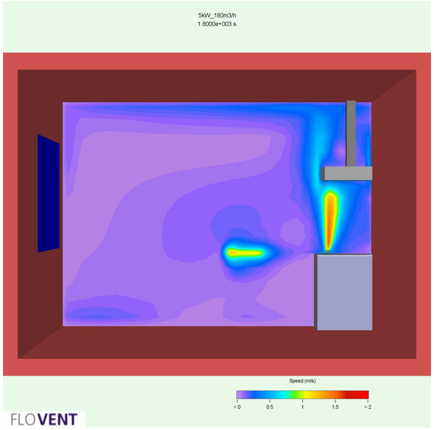

Figure 11. Indoor air temperature
(τ=30min, $\dot{V}_{ex}$ =180 m^3/h); Kajtár-Leitner (2006)

5 Conclusions

Based on results following conclusions can be made:

- Requirements for nitrogen-oxides (NO_x) concentration can not to be provided with reasonable exhaust airflow.
- Requirements for carbon-dioxide concentration can be fulfilled with 160 m^3/h exhaust airflow.
- To met IAQ requirements considerably higher ventilation rate should be provided. According calculated results, approximately 4,7 m^3/h airflow it is sufficient to ensure burning process of natural gas.

Symbols and units:

$\dot{V}_{supply}$ [m^3/h]	supply airflow
$\dot{V}_{ex}$ [m^3/h]	exhaust airflow
$\dot{V}_{fil}$ [m^3/h]	natural filtration
n [h^{-1}]	air change rate
$\dot{G}$ [mg/h]	chemical pollution load
c [$\mu g/m^3$]	indoor concentration
$c_{outdoor}$ [$\mu g/m^3$]	outdoor concentration
t_{sfi} [^oC]	surface temperature of the stove
t_{indoor} [^oC]	indoor air temperature
$t_{outdoor}$ [^oC]	outdoor air temperature
Θ [K]	over temperature
u,v,w [m/s]	indoor air velocity vectors
τ [min]	time
p [Pa]	static pressure
c [kJ/kgK]	calorific value
ρ [kg/m^3]	density
μ [kgm/s]	dynamic viscosity
ν [m^2/s]	kinematical viscosity
μ_t [kgm/s]	turbulence viscosity

References:

[1] Kajtár L.-Leitner A.-Bánhidi L.:Evaluation of IAQ in Residential KitchensBased on Laboratory and Field Studies
Lisboa, 2006. jun. 4-8.,HB 2006. 11th *International Conference on Healthy Buildings Proceedings* Volume V. 33-36 p.

[2] Kajtár L.- Leitner A. Bánhidi L.-.: Air quality and thermal comfort in kitchens.
Beijing, China, 2005. Sept. 4-9. 10th *International Conference on Indoor Air Quality and Climate Proceedings* Volume II/2. 2371-2375 p.

[3] Dr. Kajtár László - Leitner Anita: Effect of gas-range upon air quality of living spaces ROOMVENT2004; *9th International Conference University of Coimbra / Portugal; Book of Abstracts* p126-127

[4] H. B. Awbi: *Ventilation of buildings*, London. 1998 E & FN Spon

[5] Garbai L.-Némethi B.: Az épületgépészet tudományos problémái
Magyar Épületgépészet 49/3, 2000., 3-4p.

[6] Bánhidi L. - Kajtár L.:*Komfortelmélet*.
Bp, 2000. Egyetemi Tankönyv, Műegyetemi Kiadó 436 p.