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Research paper

New Approach for Estimation of Zonal Efficiency of Air Exchange Organization

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Abstract

Energy efficiency of buildings is dependent on air exchange organization. There are different methods for efficiency estimation of it. As it is shown in literature review, they have significant limitations including non-obvious physical meaning, which cause problems in validation of the results. Certain of them are not acceptable for zonal ventilation in rooms. Previous author's work introduces new approach for the efficiency estimation of air exchange in a single-zone or multi-zonal rooms, which has obvious physical meaning – relation of demands and supplied potentials. It provides the efficiency value for whole room only. In this work, by the similar approach, a method is proposed for estimation of zonal air exchange efficiency in different kind of rooms for each occupied zone separately. Additional definitions are introduced for the parameters and demands estimation in each occupied zone. The example of efficiency estimation of air exchange in a museum room with constant air volume system of air conditioning is solved. Sheltering of the keeping zone is recommended for the maximum air exchange efficiency.

Keywords: *air conditioning; air exchange; energy efficiency; ventilation; zone of room.*

1. Introduction

Air exchange organization is one of the most important factors for energy efficiency of buildings. Air exchange efficiency in rooms can be estimated by different ways taking into account different sets of factors, so they are applicable to different tasks. In previous works, an improved energy efficiency indicator for rooms with single and multiple occupied zones has been introduced. It has obvious physical meaning – relation between demands and supplied potentials. It takes into account maximum set of factors for correct estimation. In this work, the approach is used for defining zonal air exchange efficiency factor. It allows estimation of efficiency of air exchange organization for each occupied zone independently. Using it, selection of most problematic zones in multizonal rooms is possible to focus on optimization of air supply/exhaust for these zones.

2. Literature review

The authors have performed detailed literature analysis in [1]. In this work, there is brief analysis with some additions about air exchange factor and air aging. The approach of N. Sorokin, developed by M. Grimitlin and G. Pozin [1, 2, 3] is most used in post-socialist and European Union countries and partially implemented in European Union norms. It is based on air exchange factor KL (in European norms – ε_v – for CO_2 concentration only). The air exchange factor K_L (or ε_v for CO_2 concentration) is a simplex of air parameter X (air temperature $X = t$ [°C], enthalpy $X = I$ [kJ/kg], moisture content $X = d$ [g/kg], gas concentration $X = q$ [g/kg] etc.) that connects its value of leaving (exhaust) air X_ℓ, inlet air X_{in} and occupied zone X_{wz}:

$$K_L = \frac{X_1 - X_{in}}{X_{wz} - X_{in}}. \tag{1}$$

In norms of European Union [4] X is concentration of carbon dioxide [g/kg]. By M. Grimitlin, it is a factor of inlet air potential usage. As it is shown in the latest works of G. Pozin, air exchange may be approximately equal at high factor K_L and low X difference and vice versa [2]. G. Pozin [2] proposed using temperature difference $t_{wz} - t_{in}$ (in general, difference $X_{wz} - X_{in}$) in conjunction with K_L for estimation of air exchange efficiency. However, use of two independent factors simultaneously is difficult for optimization procedures. In addition, it is no wide experience of K_L use for piston ventilation at the horizontal direction of indoor air movement.

Standards of the United States of America use the indoor air quality IAQ mark and energy consumption [5]. It is not good idea to compare high energy consuming systems that provide required microclimatic conditions with low consuming systems that not provide required conditions.

The USA norm [6] gives "Zone Air Distribution Effectiveness" Ez at different options of "Air Distribution Configuration". It is an estimation of air share passed from air distributors to target zones. Too many air distribution options [7-9] require high amount of reference data. It is possible to use the author's approach based on the theory of turbulent flows by A. Tkachuk [10-12]. The effectiveness estimation does not deal with loose of temperature, moisture and other potentials of jets caused by injection of ambient air.

Today, the concept of air age, proposed by N. Brelih [13], is very popular for efficiency estimation of air exchange organization. The average age of air at a point in a room is the average time spent in the room by the air molecules that hit the point. The author obtains that near to exhaust devices the average age of air [hours] is a reciprocal of air change per hour (ACPH or ACH).

$$\tau = \frac{1}{ACPH}. \tag{2}$$

The efficiency of the air exchange ε_a [%] is defined as the ratio of the minimum possible time for replacing the air in the room τ_n to the actual air change time τ_r, equal to twice the average age of the air in the room τ:

$$\varepsilon_a = 100\frac{\tau_n}{\tau_r} = 100\frac{\tau_n}{2\tau}. \tag{3}$$

The equation (2) is valid if no circulation zones in a room or neglecting turbulent and physical diffusion. Otherwise, some air particles can be captured by a circulation zone using turbulent and physical diffusion. The air particles can circulate in the zone during undefined time (“grow old”) until they will be released to any room flow near to the circulation zone by the same principle. In this case, the equation (2) is invalid, and the actual air age cannot be calculated.

Air age is the ability estimation of the ventilation to dilute CO_2 and other gases to threshold limit value. Direct estimation of the influence of ventilation on heat and moisture is impossible. The physical meaning of this efficiency estimation is not obvious.

For detailed analysis of efficiency indicators of air exchange, please refer to the work [14]. They have the similar limitations.

In previous work [1], new air exchange efficiency estimation indicator for whole room has been proposed. Zones in a room are classified for two main types:

- **occupied zones** – zones with parameters, defined by norms, technology requirements or customer desire;
- **zones without requirements** – for air exchange efficiency, these zones are not important and may be eliminated from consideration.

Ventilated rooms by number of zones are classified as:

- **single-zone**, such as museum rooms that have historical painting on walls and ceiling;
- **dual-zone** (one occupied zone and one zone without any requirements), such as most of one-level residential, office, enterprise, and agricultural (hot-houses) rooms;
- **multi-zonal** (with at least two occupied zones), such as museums with parts for exhibition keeping and for people, atrium buildings etc. If a room has only two occupied zones and no zones without requirements, it will be classified as multi-zonal.

There are some basic definitions:

$\Delta X = X_b - X$ is an air (inlet – *in*; working zone – *wz*; leaving – *ℓ* etc.) potential by the parameter *X*, which is the difference between some basic value X_b (usually inside the room) and its value *X* in inlet or leaving air.

A parameter have corresponding gain or lack of “substance” ΔS [(kg/h)·(dimension of *X*)] (temperature $X = t$ [°C] – sensible heat $\Delta S = \Delta Q / c_p$ [kg·K/h]; enthalpy $X = I$ [kJ/kg] – full heat $\Delta S = \Delta Q_{hf}$ [kJ/h]; moisture content $X = d$ [g/kg] – moisture $\Delta S = W$ [g/h]; gas concentration $X = q$ [g/kg] – mass of the corresponding gas *M* [g/h] etc., where ΔQ [kJ/h] is sensible heat gain or loss and c_p [kJ/(kg·°C)] is specific heat of air).

Air exchange [kg/h] can be found by the common equation, obtained from the equations in [15] using the definitions above:

$$G_{\Delta S} = G_{wz} + \frac{\Delta S - G_{wz}\left(X_{wz} - X_{in}\right)}{X_1 - X_{in}} =$$

$$= G_{wz} + \frac{\Delta S - G_{wz}\left(\Delta X_{wz} - \Delta X_{in}\right)}{\Delta X_1 - \Delta X_{in}}, \tag{4}$$

where G_{wz} is flow rate [kg/h] of local suctions in the occupied zone.

Saving air parameter value X_S in a zone is a value of the parameter that corresponds to minimum expenses for inlet air treatment and minimum room demands in the range of normative or other requirements.

Effective gain (deficit) of “substance” ΔS_e is the sum of surpluses (deficiencies) of the “substance” in occupied zones at saving air parameters.

The assimilation or supply process consists of two parts:

- influence of the inlet air potential (from inlet air parameters to parameters in the occupied zones);
- influence of internal resources of the room on indoor air parameters (from the occupied zones parameters to leaving air parameters).

Thus, the basic value X_b has been accepted as ***saving average weighted air parameter of a room $\bar{X}_S$*** that is an average weighted saving air parameter in occupied zones [dimension of *X*]:

$$\bar{X}_S = \frac{\sum_{i=1}^{n} X_{S,i} V_i}{\sum_{i=1}^{n} V_i}, \tag{5}$$

where *n* – number of occupied zones, *i* – designation of each occupied zone, V_i – volume of each occupied zone [m^3]. Using average air density of each zone in the equation (5) will be more precise, but usually it is not necessary.

Effective potential of inlet air by parameter X is the difference of the saving weighted average air parameter of the room and the parameter of the inlet air [dimension of *X*]:

$$\Delta X_{in,j} = \bar{X}_S - X_{in,j}, \tag{6}$$

where *j* – number of the group of air distributors that supplies the same air parameter. The difference may be negative if there is supply of the corresponding “substance”.

The total effective potential $\Delta Y_{G,e}$ of the inlet air by parameter X is the effective potential of the inlet air by the parameter *X*, weighted by the flow rate $G_{in,j}$ [kg/h] of the inlet air [(kg/h)·(dimension of *X*)]:

$$Y_{G,e} = \sum_{j=1}^{m} G_{in,j} \Delta X_{in,e,j}, \tag{7}$$

where, *m* – number of the groups of air distributors.

The efficiency of air exchange organization by “substance” S or by parameter X is the ratio of gains or lack of the “substance” ΔS to the general effective potential of the inlet air by the parameter *X*:

$$\varepsilon_{\Delta S} = \frac{\Delta S_e}{Y_{G,e}}. \tag{8}$$

The efficiency by the equation (8) is relation of demands and supplied potentials.

A restriction [1] has been introduced for the task solution. All ventilation and air conditioning systems in the comparison strongly provide required microclimate conditions in all occupied zones. Other case cause incorrect comparison because of unequal conditions: the best solution always will be the absence of ventilation and air conditioning.

The following definitions and calculations will be performed for multi-zonal or dual-zone rooms only. For single-zone room the results of [1] are applicable.

3. Goal of the work

The goal of this research is defining a refined method for zonal efficiency estimation of air exchange organization in each occupied zone that takes into account the maximum number of influencing factors and modern energy efficiency requirements.

4. Zonal Air Exchange Efficiency Definition

Let us use the same principle of zonal air exchange efficiency as the efficiency for whole room. It is relation of demands and supplied potentials. The zone demands are the effective gain (deficit) of "substance" $\Delta S_{e,i}$ in the occupied zone *i*.

The supplied potentials is the first problem. Some air distributors can supply air into the zone *i* directly. Other ones supply air through other occupied zones or zones without requirements. Inlet air can pass through multiple zones, and it can pass some zones multiple times, until it approaches the zone *i*.

The simplest formal way is distributing the total effective potential $\Delta X_{in,e,j}$ of the inlet air between zones with weighting coefficients σ_i, abstracting from airflows in the room. Using the equation (8):

$$\varepsilon_{\Delta S,i}=\frac{\Delta S_e}{\sigma_i Y_{G,e}}=\frac{1}{\sigma_i}\varepsilon_{\Delta S}. \qquad (9)$$

The equation (9) shows very easy connection between the zonal efficiency and the efficiency for whole room. Nevertheless, if σ_i considers only formal attributes (percent of zone volume or demand), the equation (9) will have far-fetched physical meaning and no technical reason. Therefore, in this work, such formal approach will not develop.

Strong physical meaning will be kept replacing "air distributor" in the definition for whole room by "inflow" for the *i*-th zone. The basic value X_b can be accepted as the saving air parameter value $X_{S,i}$ in a zone. The air potential of inflow *g* with average parameter value X_g:

$$\Delta X_{inf,e,g}=X_{s,i}-X_g. \qquad (10)$$

The air potential of outflow *h* with average parameter value X_k:

$$\Delta X_{outf,e,h}=X_{s,i}-X_h. \qquad (11)$$

For whole room, outflows (exhaust air) are lost for the room. For zonal efficiency, outflow air can be:

- exhaust air – fully lost for the room;
- cross-flow to a zone(s) without requirements – partially lost for the room, partially treated by internal resources in the zone and returned to an occupied zone(s);
- cross-flow to an occupied zone(s) – the potential is used for ventilation of other zone(s) and should be considered.

Thus, the ***total effective potential $\Delta Y_{G,e}$ of the inflow air by parameter X*** is the effective potential of the inflow air by the parameter *X*, weighted by the flow rate $G_{inf,g}$ [kg/h] of the inflow air, minus the effective potential of the outflow air to other occupied zones by the parameter *X*, weighted by the flow rate $G_{outf,h}$ [kg/h], of the outflow air, only if the inflow or outflow air potentials perform useful effect at saving air parameters [dimension of *X*]:

$$\Delta Y_{G,e,i}=\sum_{g=1}^{p}G_{inf,g}\Delta X_{inf,e,g}-\sum_{h=1}^{q}G_{outf,h}\Delta X_{outf,e,h}, \qquad (12)$$

where, *p* – number of the inflows to current zone with usable potentials for it; *q* – number of the outflows to other occupied zones with usable potentials for them.

Analogously to the equation (8), the zonal efficiency of air exchange organization:

$$\varepsilon_{\Delta S,i}=\frac{\Delta S_{e,i}}{\Delta Y_{G,e,i}}. \qquad (13)$$

Physical meaning of the equation (8) is relation between zone demands and supplied potentials. The efficiency can be more than one in the zone with internal resources, for example, heat gains in room with air heating.

The main difficulty of the approach is necessity of calculation of cross-flows in rooms. It is possible using computational fluid dynamic simulation (CFD). As an alternative, it is possible to use G. Pozin's approach for air exchange simulation based on balance equations. At first, the scheme of flows in rooms should be accepted. After that, balance equations for each characteristic volume (jets, cross-flows, volumes of zones outside the flows etc.) should be written. The equation system may be solved to find air parameters. The approach has assumption that any characteristic volume have near-to-uniform distribution of parameters, and outflow air has the same parameter values. Therefore, the second member in the right part of the equation (12) is zero.

5. Zonal air exchange efficiency calculation

For efficiency estimation of air exchange, calculation of flows in the room are necessary. There are three options for the calculations: theoretical, simulation and experimental.

Theoretical procedure in the most quick and resource saving.

1. Jets can be calculated using standard calculation procedures [2, 16] or using the author's method based on the approach of A. Tkachuk [10-12].
2. Cross-flows can be schematically drawn by the researcher's experience. Estimation of them may be performed by balance equations [2, 3]; some additional assumptions should be applied such as uniform distribution of air parameters in sections of the cross-flows.
3. After that, the efficiency can be calculated.

Simulation can be performed using computational fluid dynamic (CFD):

1. At first, we may build a 3D model of the room with terminal devices of ventilation or air conditioning, equipment etc. We should apply correct boundary conditions to the terminal devices, equipment surfaces and the walls (heat losses, heat gains, or adiabatic) and set internal heat gains.
2. After that, simulation should be performed.
3. At zone boundaries, we should take 2D profiles of air parameter, and we should calculate inflow and outflow potentials separately on each boundary.
4. Finally, it is possible to calculate the efficiency for each zone.

Experimental definition of the efficiency is the most precise but the most time- and resource-consuming option. There are two options: laboratory and field researches

1. If laboratory researches, we should setup the experimental stand that may be as close as possible to the projected object, if field research, the step should be omitted.
2. The air parameters should be measured on a grid (the density is dependent on required accuracy) at the boundaries of the occupied zones and at the inlet terminal devices in the occupied zones.
3. We should calculate inflow and outflow potentials separately on each boundary.
4. Finally, it is possible to calculate the efficiency for each zone.

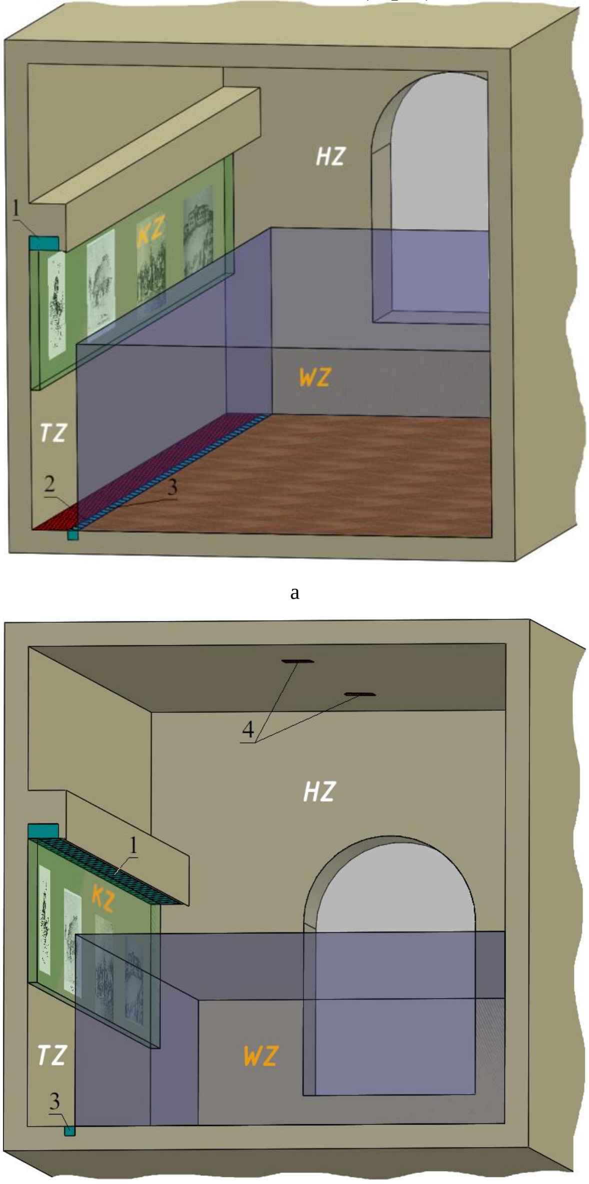
If experimental or simulation data on a flat boundary of a zone is captured using enough number of points, it is possible to estimate the potentials:

$$Y_{inf/outf}=\sum_{g=1}^{p}G_{inf/outf,g}\Delta X_{inf/outf,e,g}\approx 3600S\overline{\rho v_{n,inf/outf}\Delta X_e}, \qquad (14)$$

where *S* – the area [m^2] of the considered boundary; over-line – averaging, performed by the captured points using simple mean (for evenly distributed points only) or any quadrature rule; ρ – air density [kg/m^3] in the points; $v_{n,inf}$ or $v_{n,outf}$ – normal velocity [m/s] in the points to the boundary of inflow and outflow, accordingly (if at some point the flow has wrong direction, it is zero), ΔX_e – the air potential by the equation (10) or (11) in the points.

6. Example

Let us consider the same museum room (Fig. 1) as in the work [1].



a

b

Fig. 1: Example of air exchange organization: a – view to the floor; b – view to the ceiling: 1 – air distributor to the keeping zone (KZ) with slot downward; 2 – area of exhaust grilles from the transition zone (TZ); 3 – inlet air blow; 4 – exhaust grilles in high zone

The parameters of the room are:

- size $a \times b$ = 10×5 m;
- area $A = 10 \cdot 5 = 50$ m^2;
- height $h = 5$ m;
- volume $V = 50 \cdot 5 = 250$ m^3;
- humidity gain (to working zone) $\Delta W = 750$ g/h;
- atmospheric pressure $P = 101325$ Pa.

The room has the following zones:

- occupied zones:
  - working zone *WZ*, usually occupied by visitors and staff (sizes 10×4.5 m; area $A_{wz} = 10 \cdot 4.5 = 45$ m^2; the bottom level is at the floor; high $h_{wz} = 2$ m; volume $V_{wz} = 2 \cdot 45 = 90$ m^3; temperature t_{wz} = 20...24 °C (293.15...297.15 K), relative humidity φ_{wz} = 25...60 %, $v \le 0.3$ m/s; heat gains ΔQ_{wz} = 1000 W or 3600 kJ/h;);
  - keeping zone *KZ* with exhibition (sizes 10×0.1 m; area $A_{kz} = 10 \cdot 0.1 = 1$ m^2; the bottom level is 1,5 m above the floor; high $h_{kz} = 1.5$ m; volume $V_{kz} = 1 \cdot 1.5 = 1.5$ m^3; temperature t_{wz} = 17...19 °C (290.15...292.15 K), relative humidity φ_{wz} = 45...55 %, $v \le 0.3$ m/s);
- zone without requirements:
  - high zone *HZ* without any exhibition or people (no normative parameters);
  - transition zone *TZ* between the keeping and working zones (no normative parameters).

There is a proposition for air exchange organization (fig. 1). For ventilation of the keeping zone, $G_{in,kz}$ = 4150 kg/h of inlet air can be supplied above the keeping and transition zones with velocity $v_{in,kz}$ = 0.3 m/s as a false beam with illumination (LED strip or modules) for painting. The most of heat from the illumination is dissipated from the beam surface to the transition and high zone. No more than ΔQ_{kz} = 10 W or 36 kJ/h of the heat can reach the keeping zone. Air outlet (flow rate is $G_{out,tz}$ = 5150 kg/h) is located at the floor near to the wall below to the keeping and transition zones.

Cold air can form a wall jet above the floor. The jet can pass to the working zone above the floor, which is not good for people health. Therefore, the inlet air (flow rate is $G_{in,tz}$ = 2000 kg/h) can be released from floor air distributors in the transition zone close to the working zone to heat the cold air jet. To avoid air stagnation in the high zone, there are two exhaust grilles at the ceiling (the total flow rate is $G_{out,hz}$ = 1000 kg/h). This air exchange organization has been successfully checked for provision of the normative air parameters. The task is to check the efficiency by sensible heat for cooling period.

1. The air exchange is accepted as quick.

2. Calculation of the heat assimilation demand in the keeping and working zones, correspondingly:

$$\Delta S_{e,kz} = \Delta Q_{wz} / c_p = 36 / 1{,}005 = 35{,}82 \text{ kg·K/h};$$

$$\Delta S_{e,wz} = \Delta Q_{wz} / c_p = 3600 / 1{,}005 = 3582 \text{ kg·K/h}.$$

3. Simulation of the room is performed on 3D model (Fig. 1) using k-ε model for turbulent flows. For simplification, we did not draw the exhaust devices on the floor. We applied the boundary condition “outlet opening” to the part of the floor between the air inlet and the wall, in which the devices are located. Otherwise, the model require very dense calculation mesh without significant improvement in accuracy. The results are on the Fig. 2-4.

4. Processing of the results is shown in the Table 1. Destinations of all outflows from the occupied zones are in the zones without requirements. Therefore, the flows are not calculated. The keeping zone has average temperature 291.05 K or 17.90 °C. It has inflows only from the vertical boundary with the potential $Y_{inf,WZ\leftarrow KZ,HZ}$ = 1113 kg·K/h. The working zone has average temperature 294.53 K or 21.38 °C. It has inflows from the transition and high zones with the potentials, correspondingly, $Y_{inf,WZ\leftarrow TZ}$ = 13368 kg·K/h and $Y_{inf,WZ\leftarrow HZ}$ = 19150 kg·K/h.

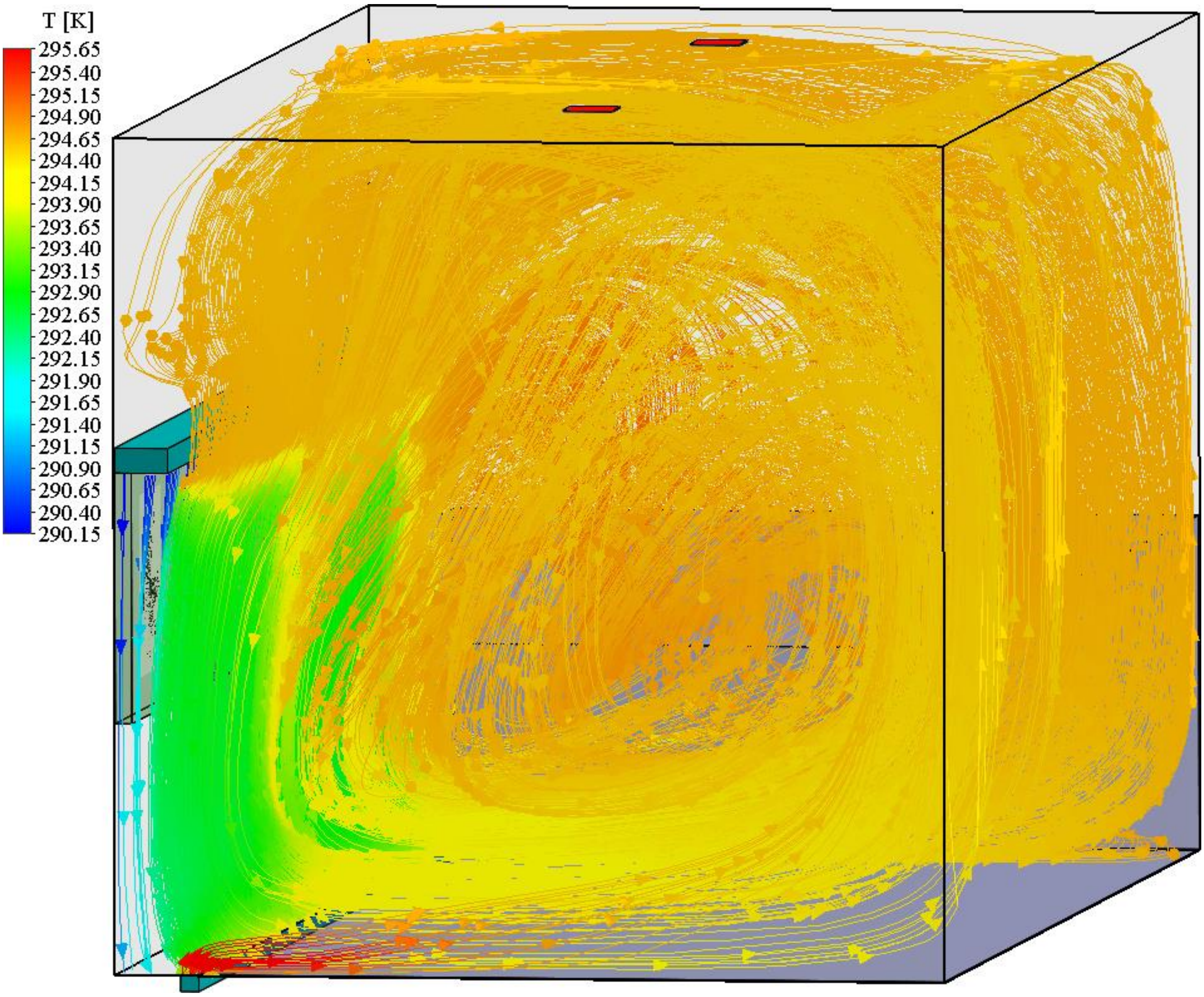


Fig. 2: Lines of flow in the room

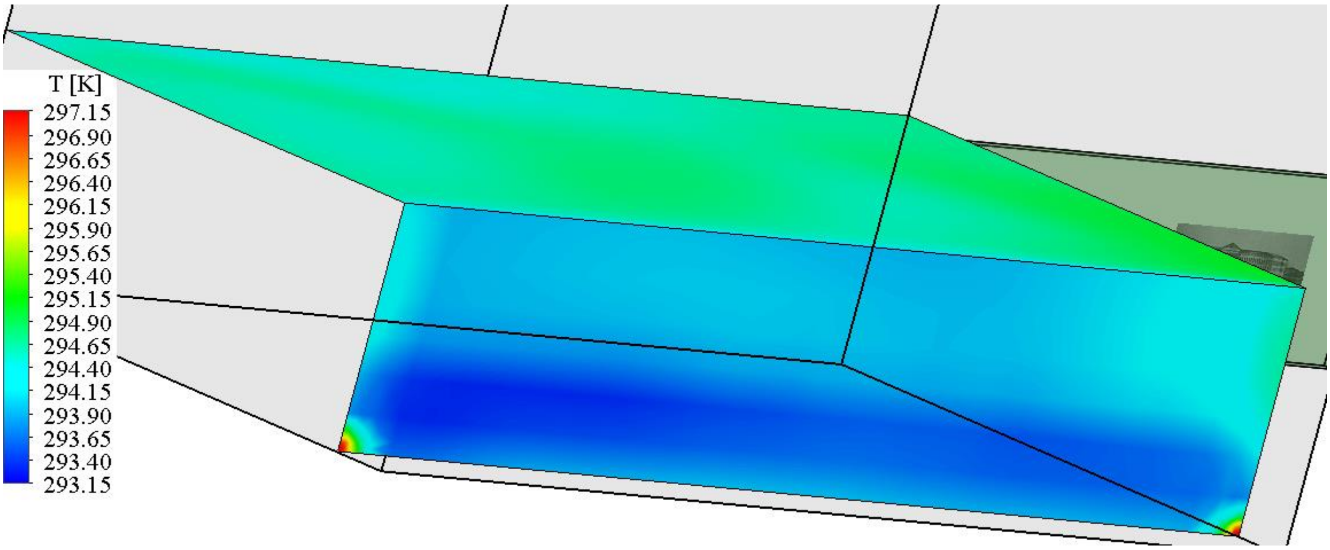


Fig. 3: Temperature distribution at the boundaries of the working zone

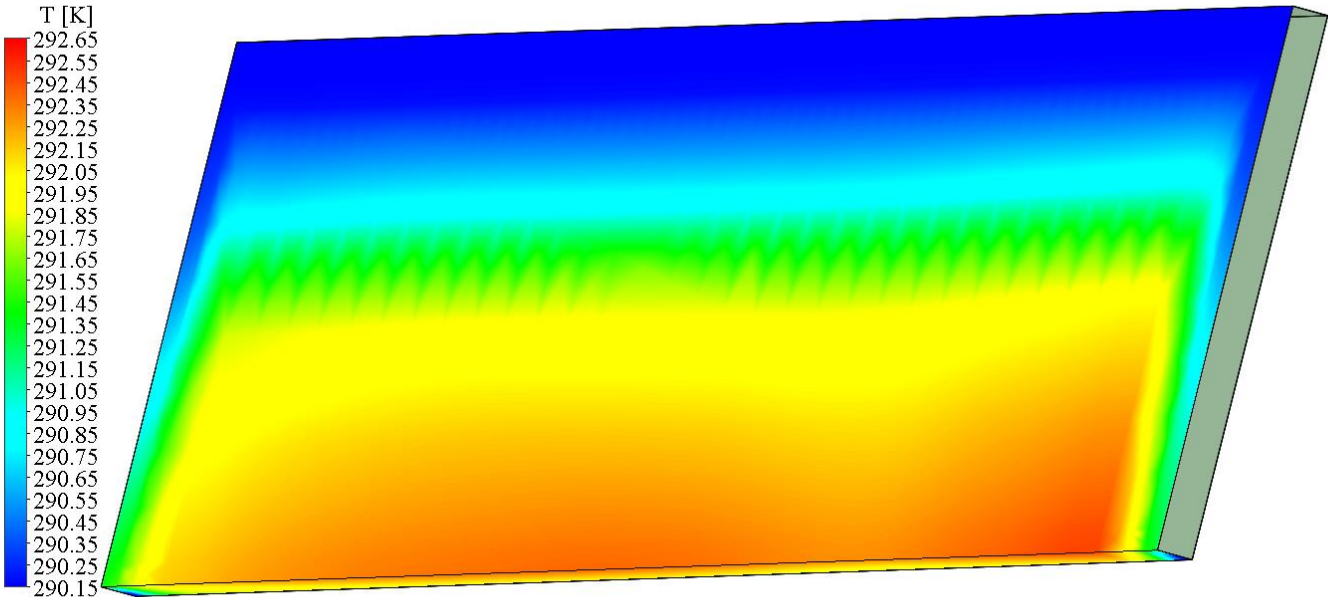


Fig. 4: Temperature distribution at the boundaries of the keeping zone

Table 1: Fragment of the table for processing the results for the boundaries of the zones

Number	Coordinate [m]			Density	Temperature			Normal velocity	$\rho\ v_x\ \Delta T$
	x	y	z	ρ [kg/m^3]	T [K]	θ [°C]	potential $\Delta T = \theta_s - \theta$ [K]	v_x, v_z [m/s]	kg·K/(m^2·s)
The vertical boundary of the working zone to the transition zone: θ_s = 24.00 °C; S = 20.000 m^2; inflow – $v_x < 0$									
1		– 1.500	– 4.975	1.200	294.26	21.11	2.89	0.001	0.000 (outflow)
2		– 1.550	– 4.975	1.200	294.25	21.10	2.90	0.000	0,000 (outflow)
3		– 1.600	– 4.975	1.200	294.21	21.06	2.94	– 0.007	0.023
4		– 1.650	– 4.975	1.200	294.16	21.01	2.99	– 0.007	0.023
5		– 1.700	– 4.975	1.200	294.10	20.95	3.05	– 0.007	0.024
6		– 1.750	– 4.975	1.201	294.03	20.88	3.12	– 0.007	0.024
7		– 1.800	– 4.975	1.201	293.97	20.82	3.18	– 0.007	0.025
					·	·	·		
8200			4.975	1.188	297.14	23.99	0.01	0.000	0.000
Average $(\rho\ v_x\ T)_{av}$ [kg·K/(m^2·s)]									0.186
Total effective potential $\Delta Y_{G,e} = (\rho\ v_x\ T)_{av}\ S$ [kg·K/s]									13368
The horizontal boundary of the working zone to the high zone: θ_s = 24.00 °C; S = 45.000 m^2; inflow – $v_z < 0$									
1	– 0.250		– 4.975	1.198	294.60	21.45	2.55	– 0.019	0.057
2	– 0.200		– 4.975	1.198	294.60	21.45	2.55	– 0.019	0.057
3	– 0.150		– 4.975	1.198	294.60	21.45	2.55	– 0.019	0.057
4	– 0.100		– 4.975	1.198	294.60	21.45	2.55	– 0.019	0.057
					·	·	·		
67	– 1.300		– 4.975	1.198	294.60	21.45	2.55	0.006	0.000 (outflow)
68	– 1.350		– 4.975	1.198	294.61	21.46	2.54	0.006	0.000 (outflow)
					·	·	·		
18200	– 2.150		4.975	1.198	294.72	21.57	2.43	0.000	0.000
Average $(\rho\ v_x\ T)_{av}$ [kg·K/(m^2·s)]									0.118
Total effective potential $\Delta Y_{G,e} = (\rho\ v_x\ T)_{av}\ S$ [kg·K/s]									19150
The vertical boundary of the keeping zone to the transition (under 2 m) and the high (above 2 m) zones: θ_s = 19.00 °C; S = 15.000 m^2; inflow – $v_x > 0$									
1		– 0.225	4.975	1.215	290.58	17.43	1.57	0.023	0.044
2		– 0.275	4.975	1.214	290.63	17.48	1.52	0.022	0.041
3		– 0.325	4.975	1.214	290.68	17.53	1.47	0.022	0.039
4		– 0.375	4.975	1.214	290.73	17.58	1.42	0.021	0.037
					·	·	·		
253		– 0.825	4.575	1.208	292.17	19.02	– 0.02	0.015	0.000 (unusable potential)
254		– 0.875	4.575	1.208	292.22	19.02	– 0.07	0.015	0.000 (unusable potential)
					·	·	·		
6000		0.475	– 4.975	1.216	290.15	17.00	2.00	0.003	0.006
Average $(\rho\ v_x\ T)_{av}$ [kg·K/(m^2·s)]									0.017
Total effective potential $\Delta Y_{G,e} = (\rho\ v_x\ T)_{av}\ S$ [kg·K/s]									1113
The horizontal boundary of the keeping zone to the transition zone: θ_s = 19.00 °C; S = 1.000 m^2; inflow – $v_z > 0$									
1	2.475		– 4.975	1.216	290.22	17.07	1.93	– 0.300	0.000 (outflow)
2	2.425		– 4.975	1.213	290.95	17.80	1.20	– 0.290	0.000 (outflow)
3	2.475		– 4.925	1.215	290.41	17.26	1.74	– 0.287	0.000 (outflow)
					·	·	·		
400	2.425		4.975	1.214	290.80	17.65	1.35	– 0.300	0.000 (outflow)
Average $(\rho\ v_x\ T)_{av}$ [kg·K/(m^2·s)]									0.000
Total effective potential $\Delta Y_{G,e} = (\rho\ v_x\ T)_{av}\ S$ [kg·K/s]									0

5. The efficiency calculation. By the equation (12) for keeping and working zones, accordingly,

$$\Delta Y_{G,e,kz} = Y_{inf,\ WZ\leftarrow KZ,HZ} = 1113\ \text{kg}\cdot\text{K/h};\ ;$$

$$\Delta Y_{G,e,wz} = Y_{inf,WZ\leftarrow TZ} + Y_{inf,WZ\leftarrow HZ} = 13368 + 19150 = 32518\ \ \text{kg}\cdot\text{K/h}.$$

By the equation (13), the efficiency is, correspondingly,

$$\varepsilon_{\Delta S,kz} = \frac{\Delta S_{e,kz}}{\Delta Y_{G,e,kz}} = \frac{35.82}{1091} = 0.033;$$

$$\varepsilon_{\Delta S,wz} = \frac{\Delta S_{e,wz}}{\Delta Y_{G,e,wz}} = \frac{3582}{32518} = 0.110.$$

Very low efficiency is caused by three reasons:

- inlet air in the keeping zone assimilates heat gains of air inflow from the working zone through the transition zone, which caused by the jet injection;
- huge air exchange amount to assimilate the parasitic heat gains in the keeping zone and to heat the cross-flow air to the working zone;
- in the working zone, the average temperature is very low comparably to the effective temperature to minimize the temperature of cross-flow to the keeping zone through the transition zone;

Avoiding the problem is possible by sheltering the keeping zone using glass. It is enough to put vertical glass screen in front of the keeping zone. Transition zone is not necessary in this case. This makes possible using standard displacement or pump ventilation in each zone with near to one efficiency. Showcases with organized internal air exchange allow minimizing the sizes of keeping zone, which causes minimum assimilation demands. In addition, the solutions are more secure, because there is no direct access to the exhibition for visitors. In other side, the solutions cause worsening of perception because of light spots, non-ideal flatness and clearness of the glass.

7. Conclusions

Using the authors approach for estimation of efficiency of air exchange organization, we propose the method for estimation of zonal air exchange efficiency. The advantage of it is obvious physical meaning – relation between demands and supplied potential. The method allows correct calculation of air exchange efficiency in each occupied zone in rooms.

Application of the method to a museum room shows the recommendation of sheltering of the exhibition. It avoids cross-flow to the keeping zone of the air with higher temperature. In this case, displacement or pump ventilation is possible with near to one efficiency. However, this degrade the perception of the exhibition because of light spots, curvature and non-ideal clearness of the glass.

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