A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T

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THE INFLUENCE OF THE LOCALIZATION OF OUTLETS ON THE AIR DISTRIBUTION AND THE PROPAGATION OF CONTAMINANTS IN ROOMS WITH MIXING VENTILATION

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Abstract

The paper presents the results of numerical investigations aiming at an assessment of the influence of the localization of outlets in ventilated room on the condition arising in the occupied zone. For this purpose the computer codes Flovent and Airpak Fluent were used, basing on the technique of computational fluid dynamics CFD and permitting to predict the flow of air and contaminants. The numerical calculations concerned mixing ventilation with tangential flows of supplied air. Three enclosures were dealt with in the paper, differing in their dimensions, localization of the inlets and kind of emitted contaminants. In the course of investigations the localization of the outlets was changed, observing simultaneously distribution of the air velocity in the large industrial hall, distribution of the air velocity and concentration of carbon dioxide in a small office room and distribution of the airflow parameters and the relative humidity in the covered swimming pool. Basing on these investigations the conclusion has been drawn that the localization of the outlets does not influence the air distribution in the occupied zone. Suggestions have been put forward concerning the proper choice of the localization of the outlet from the viewpoint of removing gaseous contaminants and water vapour.

Streszczenie

W artykule przedstawiono wyniki badań numerycznych mających na celu ocenę wpływu lokalizacji wywiewników w pomieszczeniu wentylowanym na warunki wytworzone w strefie przebywania ludzi. W badaniach wykorzystano programy komputerowe Flovent i Airpak Fluent, bazujące na technice numerycznej mechaniki płynów CFD i służące do prognozowania przepływów powietrza i zanieczyszczeń. Obliczenia numeryczne dotyczyły wentylacji mieszającej z przepływami stycznymi powietrza nawiewanego. Zakresem artykułu objęto trzy obiekty, różniące się wielkością, położeniem nawiewników oraz rodzajem emitowanych zanieczyszczeń. W obiektach w trakcie badań zmieniano lokalizację wywiewników i obserwowano wpływ tej zmiany: na rozkład prędkości powietrza w dużej hali przemysłowej, rozkład prędkości powietrza i stężenia dwutlenku węgla w małym pomieszczeniu biurowym oraz rozkład prędkości i wilgotności względnej w hali pływalni. Na tej podstawie wyciągnięto wniosek o braku wpływu usytuowania wywiewników na rozkład prędkości powietrza w strefie przebywania ludzi oraz podano wskazówki, co do wyboru lokalizacji najkorzystniejszej z punktu widzenia usuwania zanieczyszczeń gazowych i pary wodnej.

Keywords: **Numerical calculation CFD; Mixing ventilation; Ventilation openings; Air distribution; Contaminant; Moisture.**

1. INTRODUCTION

A correct assessment of the ventilation by the residents of the ventilated chambers depends on the adequate choice of the conception of air distribution. It is generally known that the proper choice of the inlets and the parameters of the jets supplied through them is an essential factor affecting the airflow inside the chamber. There are many uncertainties among the designers, concerning the influence of the outlets, particularly as to the place of installing them. This problem has been solved in the case of displacement ventilation, where the localization of the outlet is conditioned by the natural direction of the flow of air and contaminations [1], [2]. As far as mixing ventilation is concerned, this problem is still controversial.

The suction of air through the outlet causes the formation of specific velocity profiles around it, expressed by Dalla Valla‘s experimental equations, indicating a local character of the effect of this opening [3]. Thus, the exhaust jets ought not to affect essentially the airflow inside the ventilated room farther away from the outlet. Not all designers are, however, fully convinced in this case. Investigations, which have been carried out so far in this domain have been only fragmentary and may have even involved erroneous conclusions [4].

The quoted analysis aimed at providing an answer to the question whether concerning the air distribution in case of mixing ventilation, special attention ought to be paid to the localization of the outlet. In the investigations the technique of computational fluid dynamics (CFD) [5] was applied. Basing on this method the computer code permitted to calculate the distribution of the parameters of air, among other average velocity, the concentration of gaseous contaminants and the relative humidity.

2. RESULTS AND DISCUSSION

For the purpose of numerical predictions three ventilated enclosures were selected, in which the inlet jets affected a tangential flow. These chambers differed from each other in their dimensions and the localization of the inlets and outlets, as well as the kind of emitted contaminations of the air.

2.1. The influence of the localization of outlets in a large enclosure

The airflow in a large enclosure was numerically predicted making use of the CFD code Flovent (*www.flovent.com*). The aim was to investigate the influence of the height of the localization of the outlets and their position in relation to the inlets on the distribution of the ventilation air and of the air parameters in the occupied zone.

The object of the investigations was a repeatable fragment of an industrial hall [6], as shown in the scheme (Fig. 1), with the following dimensions: length L = 18 m, width B = 9 m, height H = 15m. The investigations concerned steady and isothermal conditions. The air was supplied to the hall through three supply grids, size 0.4×0.275 m, situated in the wall along the hall at the height of 3.5 m (0.23H) and at the distance of 6 (0.33L) m from each other. The air change rate n in the enclosure amounted to 2.9 h^{-1}. One single outlet, size 0.7×0.7 m, was positioned at two different heights of 0.5 m (0.03H) (object I) and 12 (0.8H) m (object II) half way along the hall. Besides, the case with three outlets, size 0.4×0.4 m, situated at the same height as the inlets and in their vicinity was analyzed (object III). Such position of these openings is characteristic for air-heater units, frequently applied in large ventilated objects.

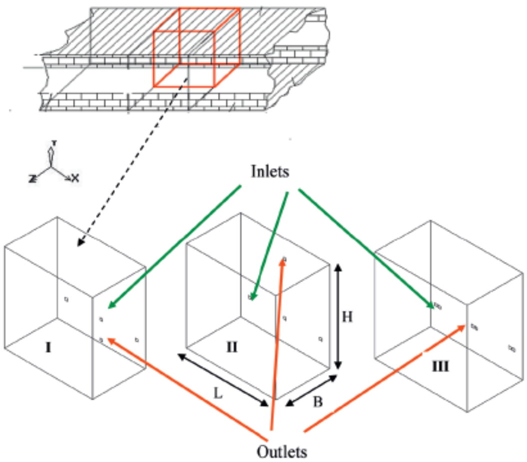

Figure 1.
Scheme of the test fragment of the industrial hall for various heights of the outlets localization

Fig. 2 illustrates the airflow pattern in the hall concerning three localization of the outlets as the iso surfaces of average velocity of air 1m/s and 0.35 m/s.

Fig. 3a shows distribution of the average velocity on the level 1.5 m (0.1H) above the floor and Fig. 3b distribution of isovels in the range of 0.15-0.35 m/s in this cross-section.

Basing on the predicted distributions, the characteristic values of average velocity have been quoted, in relation to the supply velocity V_N = 6 m/s (Table 1). The mean values V_m amounted to 4.3% and 4.5%, whereas the maximum values V_{max} were contained within the range of 9.5% and 10.7%. The minimum values V_{min} amounted to 2.3% and 2.8%. The values

Table 1.
Characteristic values of the average velocity in test large hall for various heights of the outlets localization

Variant	P'%	P"%	V_m/V_N	V_{max}/V_N	V_{min}/V_N	Modal	
						$\%V_N$	Frequency
I	90	88	4.5	10.7	2.8	4.5	10%
II	91	90	4.3	9.5	2.3	4.2	12%
III	92	91	4.3	9.5	2.8	4.3	12%

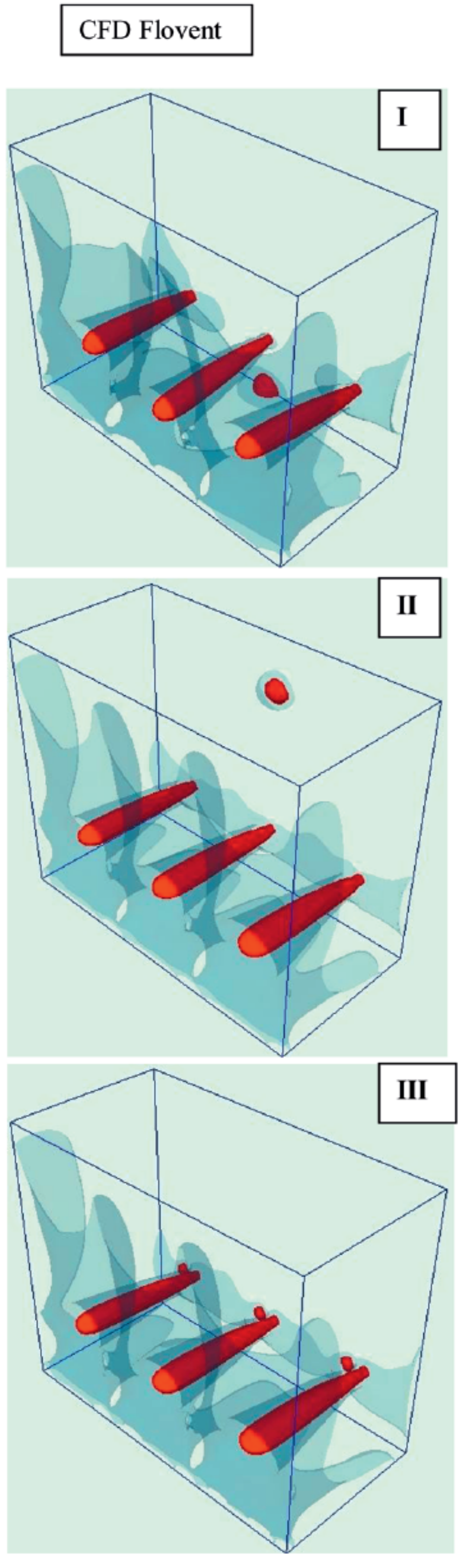

Figure 2.
Distribution of the average velocity iso surfaces: 1 m/s and 0.35 m/s in the large hall for various heights of the outlets localization

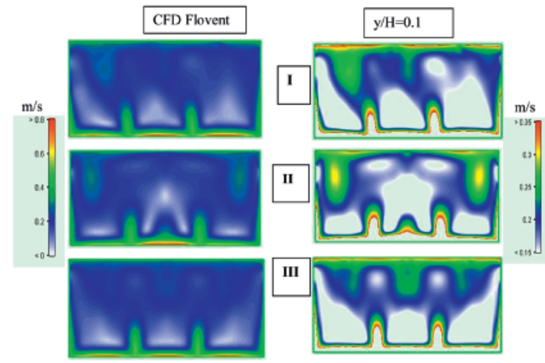

Figure 3.
Distribution of the average velocity in the occupied zone of the large hall for various heights of the outlets localization:
a) map of the average velocity
b) isolines of the average velocity in the range 0.15-0.35 m/s

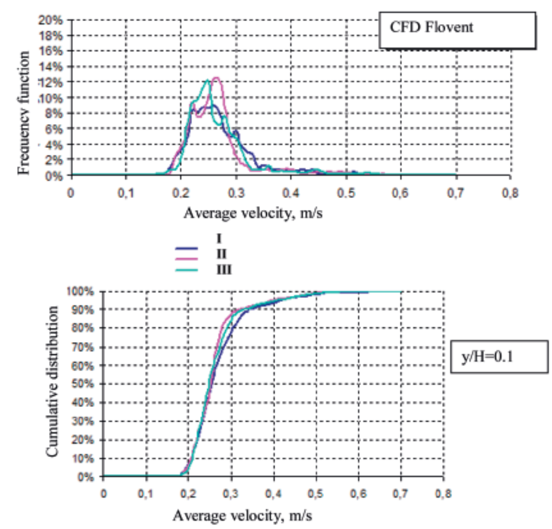

Figure 4.
Comparison of the profiles of frequency function and cumulative distribution of average velocity in the occupied zone of the large hall for various heights of the outlets localization

of the function P", defining the probability of the occurrence of the average velocity in the range of 0.15÷0.35 m/s have also been compared. These values oscillated in the range of 88% to 91%. So no larger differences between the results concerning the various localizations of the outlets have been observed.

Even when the profiles of the frequency function of the average velocity and cumulative distribution of this parameter on the level 1.5 m (0.1H) were compared for various height of outlet localization, no considerable difference could be observed in their shape (Fig. 4).

Also the values of function P', providing information about the probability containing values of the average velocity within the range [(V_m-0.1); [(V_m+0.1)], calculated for each described variant (Table 1), did not indicate any differences between the respective height of localization. The values of this probability oscillated merely between 90% and 92%.

Thus, the conclusions can be drawn that in case of large ventilated enclosure the height of the localization of the outlets does not affect the average velocity of air in the occupied zone.

2.2. The influence of the localization of outlets in a small ventilated room

The airflow in a small room, e.g. an office or some room in a flat, was also predicted numerically applying the CFD code Flovent in order to find out whether the decrease of the dimensions of the ventilated chambers results in an increase of influence of localization of outlets on the distribution of the airflow parameters in the occupied zone. Moreover, the analyses also accounted for the influence of the outlets on the concentration of gaseous contaminants.

The calculation concerned room as shown in the scheme (Fig. 5), with the following dimensions: length L = 6 m, width B = 6 m, height H = 3 m, at the steady flow under isothermal conditions with a temperature of 20°C. The object contained a point source of gaseous contaminant carbon dioxide, localized in the geometrical centre of the floor (z = 3 m). The intensity of the emission amounted to 10 mg/s, which corresponded to the evolution of this gas by one person.

The ventilation air was supplied through a rectangular grid with the dimension 0.15m×0.1m, localized half way in the left wall of the room at a distance of 0.7 m (0.23H) from the ceiling. The supply velocity of air amounted to V_N = 5.2 m/s, which corresponded to the air change rate z = 2.6 h^{-1}. The turbulence intensity in the inlet was 30%. Numerical calculations were carried out for four typical localizations of the outlet at the top and the bottom of left and right-hand wall. The shape and dimensions of the outlet were the same as those of the inlet.

The results of these investigations have been gathered in Fig. 6, for various localization of the outlet (variants A-D), in the form of maps of the average velocity in the vertical longitudinal cross-section passing through the centre of the width of the ventilating openings. Comparing these airflow pattern it was found that the position of the outlet does not affect essentially the flow of the supply jet and in the remaining parts of the room. When the outlet was situated above the inlet (variant D), no "short circuit" between these opening was to be observed.

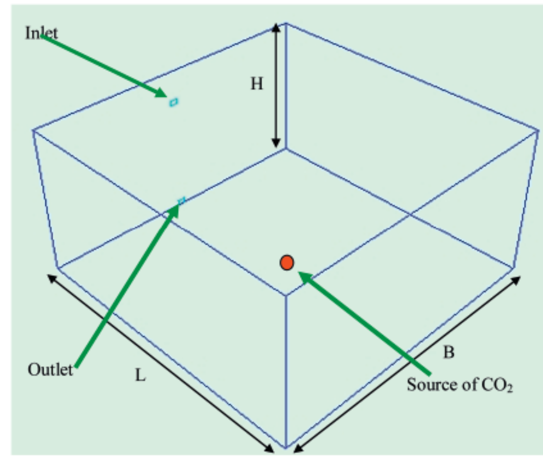

Figure 5.
Scheme of the test small office room

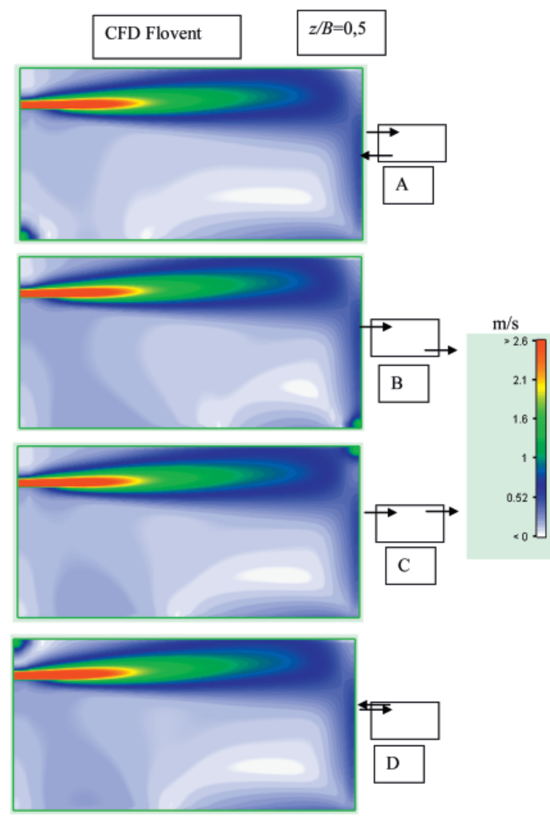

Figure 6.
Maps of the average velocity in the middle vertical longitudinal section of the small room with schemes of ventilation openings localization

The influence of the localization of the outlet on the characteristic values of the average velocity in the

Table 2.
Parameters characterizing distribution of the average velocity and ventilation effectiveness in the occupied zone of the test small room for various localizations of the outlets

Variant	*CRE*	V_{max}		$V_{1.5}$		$V_{0.15}$	
		m/s	% V_N	m/s	% V_N	m/s	% V_N
A	0.885	0.342	6.56	0.084	1.61	0.183	3.51
B	0.949	0.334	6.41	0.079	1.52	0.175	3.36
C	0.795	0.308	5.91	0.078	1.50	0.170	3.26
D	0.870	0.340	6.53	0.083	1.59	0.181	3.47

occupied zone is shown in Table 2.

The maximum values of the average velocity V_{max} in the occupied zone oscillated from 5.91% V_N at the outlet at top of right-hand side (variant C) to 6.56% V_N at the bottom of left-hand outlet, similarly as in case of the mean value of the average velocity on the levels 1.5 m (0.5H) ($V_{1.5}$) and 0.15 m (0.05H) ($V_{0.15}$).

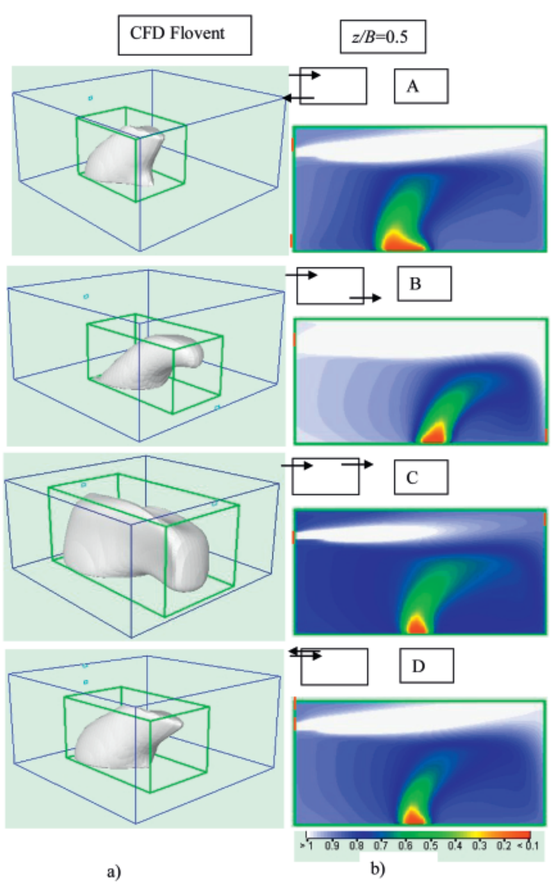

Figure 7.
Influence of the outlets localization on the distribution of:
a) iso surfaces of the CO_2 concentration of 130 ppm in the room
b) the index LAQI in the middle vertical longitudinal section of the room

Here the lowest values normalized by the supply velocity also occurred at the top right-hand outlet (variant C), i.e. 1.5% and 3.26 % and the highest at the bottom left-hand outlet (variant A), i.e. 1.61% and 3.31%. Thus, it may be concluded that the differences were rather inconsiderable and that in a small room the localization of the outlet did not matter much.

The contrary, however, was the case with gaseous contaminants. In order to assess the influence of the localization of the outlet the iso surfaces of the boundary concentration, amounting to 130 ppm (Fig. 7a), separating a region of direct influence of the source, was observed. As has been found, the smallest region of considerable air pollution occurred in both cases of the outlet, situated at the bottom (variant A) and the largest one, when the outlet was localized at the top of the opposite wall to that of the inlet (variant C).

Next the distribution of the local air quality index LAQI was analysed (Fig. 7b). This index measures how contaminated the air in local point is (the air being exhausted from the whole enclosure [7]). For a perfect mixing system LAQI is equal 1. For real mixing system the higher the value at the local point, the better is the capability of the ventilation system in removing contaminated air from that point. Thus it was found that the best air quality occurred in the occupied zone when the outlet was localized at the bottom opposite to the inlet (variant B).

The values of this index, calculated for the mean contaminant concentration in the room, called the contaminant removal effectiveness *CRE*, have been gathered in Table 2. The conditions prevailing in the room were the more favourable, the value of CRE is higher. This was the case when the outlet was situated at the bottom of the wall opposite to the inlet (variant B). The localization of the outlet at the same side at the top (variant C), however, promoted the equalization of the contaminant concentration in the rather high degree, corresponding to the lowest value of *CRE*. The application of the outlet on the left-hand side above the inlet (variant D) or just above the floor (variant A) did not influence much the values of the analyzed parameters. They were being kept on a medium level.

The performed analyses lead to the conclusion that from the viewpoint of the effectiveness of removal of gaseous contaminants it is most expedient to localize the outlet opposite to the inlet at the bottom (variant B). The localization on the same side as the inlet (variant A) proved to cause redundantly a return flow of the polluted air through the room, without the *CRE* increasing. Therefore, it is no recommendable.

2.3. The influence of the localization of outlets in chambers with a considerable moisture gain

The next subject of investigations was an enclosure with high moisture gain in the form of water vapour. Making use of the CFD code Airpak Fluent (*www.ansys.com*) a numerical model of a typical covered swimming pool was developed, the dimensions of which amounted to L = 37m in length, B = 24 m in width and H = 8 m in height. The proper swimming pool was 25 m long, B = 12.5 m wide and 1.1÷3.5 m deep. The scheme of the modelled enclosure has been presented in Fig. 8. The air was supplied into this enclosure vertically through a slot inlet at the bottom just under the window along the hall. The air volume flow rate warranted an air change rate $z=5h^{-1}$, as required in case of such objects. The air was removed from the hall through two outlets 0.5×0.5 m in size, positioned in 6 different variants, in Fig. 8 denoted by numbers 1 to 6. The water vapour arising from the pool was lighter than air and escaped upwards. Therefore, it was preferable to localize these openings at the top of the hall. In two variants 5 and 6, additionally, outlet slot have been applied at the bottom on the water level, one sided one under the wall and two sided one along the banks of the pool. In this way 10% of air volume flow rate was cleared out. Such recommendations are frequently suggested to the designers by sanitary staffs.

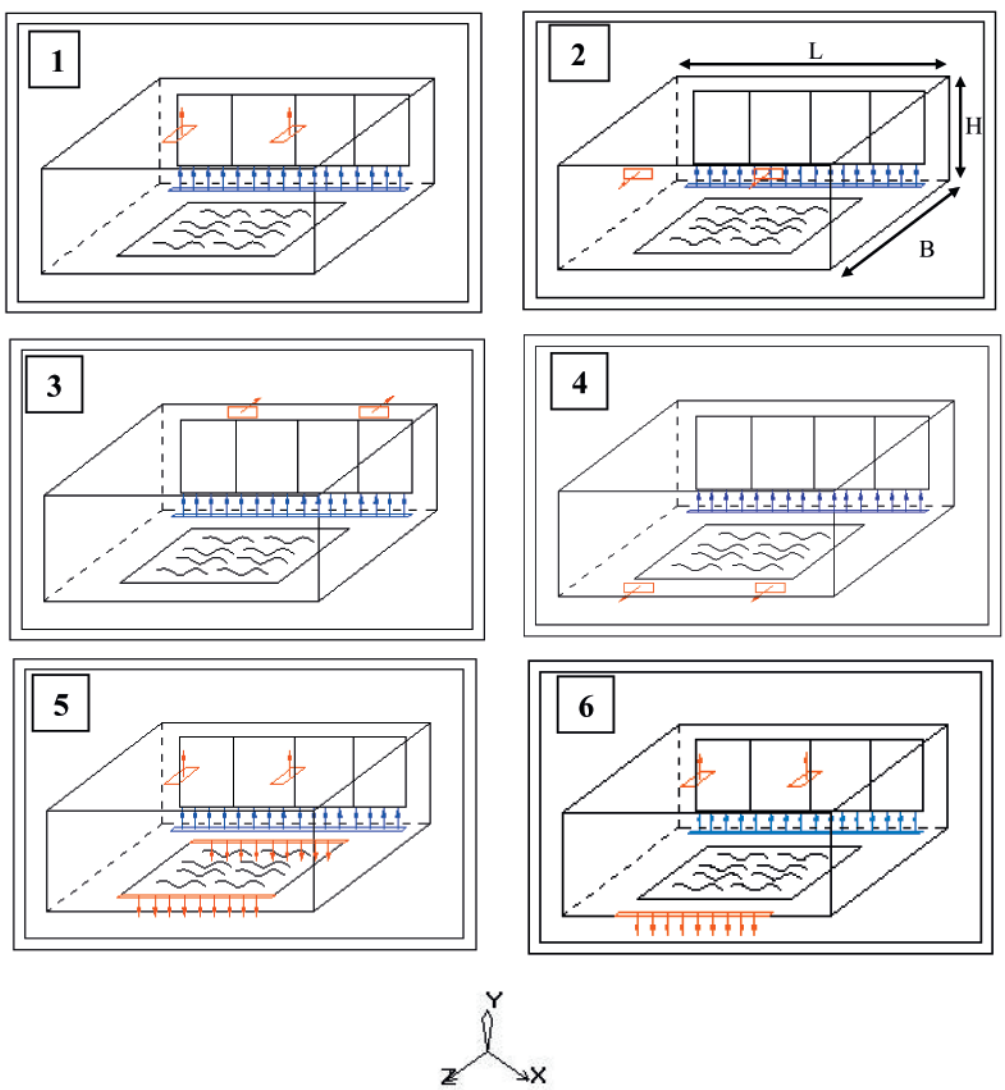

Figure 8.
Schemes of the test swimming pool for the various localizations of the outlets

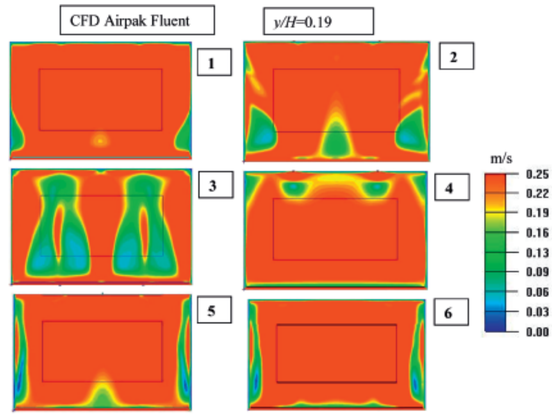

Figure 9.
Maps of the average velocity in the occupied zone of the swimming pool for various localizations of the outlets [7]

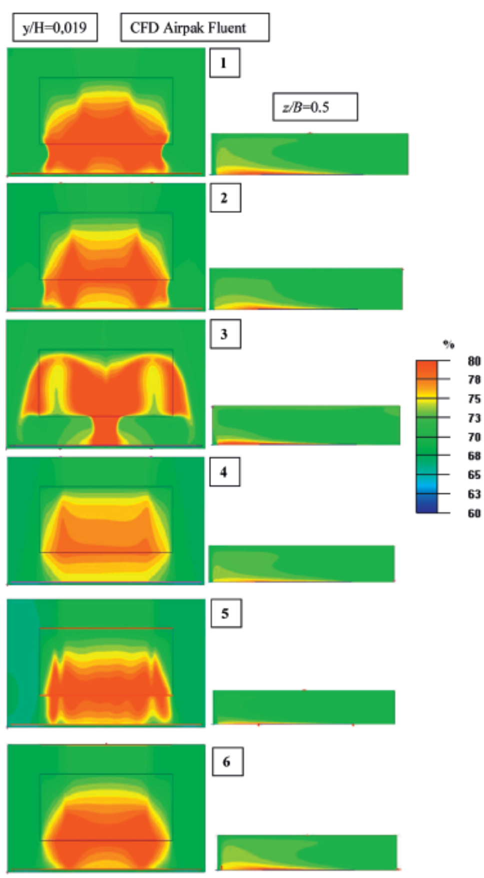

Figure 10.
Maps of the relative humidity in the occupied zone of the swimming pool for various localizations of the outlets [7]:
a) in horizontal section at the height 0.15 m
b) in the middle vertical longitudinal section

The results of numerical calculation presented as the distribution of the average velocity of the air in the occupied zone at the height 1.5 m (0.19H), concerning all the calculated variants have been quoted in Fig. 9. Similarly as in the case of the enclosures dealt with above, no essential influence of changing the position of the outlets on the distribution of the average velocity of air was to be observed. Only in case 3, when the outlet was placed at the same side as the inlet, the average velocity of air was reduced and in result stagnant zones emerged in large part of the occupied zone, apparently due to reduced access of air into this zone, some of the air having partially been sucked up by the outlets.

The influence of the localization of the outlets on the distribution of the relative humidity is evident in Fig.10 in horizontal cross-sections on the level 0.15 m (a) and in the central longitudinal section of the hall (b). The obtained flow patterns were similar and the ranges of relative humidity and mean values of this parameters as well as the specific humidity approached each other in all the variants, as may be seen in Table 3. Only in variant 3 the maximum relative humidity was higher, probably due to the weaker ventilation of the zone. The lowest range of values of this parameter was observed in the bottom part of the zone in variant 4, where the outlets were positioned below. This means that such a solution promoted the removal of water vapour from the lower part of the enclosure. The application of additional slot inlets at the pool in variant 5 affected to some extent a reduction of the relative humidity in the higher part of the hall, but the reduction of these parameters values in the occupied zone was inconsiderable. As it results from investigation [7], however, such a solution contributed to a reduction of the concentration of chlorine above the pool by about 20%.

Table 3.
Characteristic values of relative and specific humidity in the occupied zone of the swimming pool for various localizations of the outlets [7]

Variant		1	2	3	4	5	6
Relative humidity %	maximum	84	83	95	78	82	83
	minimum	66	66	67	70	65	66
	mean	72	71	74	72	70	72
Specific humidity. kg H_2O /kg d.a	mean	0.01495	0.01480	0.01533	0.01495	0.01465	0.01491

3. CONCLUSIONS

Numerical investigations concerning the influence of the localization of the outlets on the distribution of air and gaseous contaminants, as well as on the moisture in case of mixing ventilation lead to the following conclusions:

1. Independently of the dimensions of the enclosure, no essential influence of the localizations of the outlets on the distribution of the air velocity was observed in the occupied zone.
2. In case of a lateral air supply from above into enclosure with a source of gaseous contaminant heavier than air it is most expedient to localize the outlet at the bottom of the wall opposite to the inlet.
3. The distribution of the relative humidity in room with high moisture gain (when the air is supplied at the bottom and the outlets is at the top) is not affected by the place of installation of these openings. However, the localization of the outlet in the lower part of the enclosure may contribute to decrease of the values of the relative humidity in the occupied zone.

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