THE INFLUENCE OF THE INLET AND OUTLET CONDITIONS ON THE AIR VELOCITY DISTRIBUTION IN A LARGE INDUSTRIAL HALL

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Abstract
The paper presents the results of investigations aiming at an assessment of the effect of various factors connected with the supply and exhaust of ventilation air in the typical industrial hall at mixing ventilation with tangential flows of supplied air on the velocity distribution in the occupied zone. For this purpose the computer codes Flovent were used, based on the technique of computational fluid dynamics CFD and permitting to predict the airflow. The method of assessing and comparing the velocity distribution was suggested. The validation of the numerical calculations concerning the occupied zone was presented, basing on the measurements in the physical model of this hall. In the course of investigations the supply air velocity, the distance between the inlets, the angle of spread of the vanes in the inlets and the localization of the outlets was changed at isothermal and non-isothermal airflow, observing simultaneously the distribution of the air velocity in occupied zone. Based on these investigations the conclusions have been drawn that such factors as height of the positioning of the outlets or the spread of the vanes are in this case of less importance. Much more importance must be assigned to the supply air velocity and spacing of the inlets. These conclusions may constitute guidelines for designers of ventilation systems.

Streszczenie
W pracy przedstawiono wyniki badań mających na celu ocenę wpływu różnych czynników związanych z nawiewem i wywiewem powietrza wentylacyjnego w typowej hali przemysłowej z wentylacją mieszającą ze stycznym przepływem powietrza nawiewanego na rozkład prędkości w strefie przebywania ludzi. W badaniach wykorzystano program komputerowy Flovent, bazujący na technice numerycznej mechaniki płynów CFD, pozwalający prognozować przepływy powietrza. Zaproponowano metodę oceny i porównania rozkładów prędkości. Przeprowadzono walidację obliczeń numerycznych dotyczących strefy przebywania, wykorzystując w tym celu wyniki pomiarów w modelu fizykalnym tej hali. W trakcie badań numerycznych, prowadzonych w warunkach izotermicznych i nieizotermicznych, zmieniano prędkość nawiewania powietrza, odległość pomiędzy nawiewnikami, kąt rozwarcia łopatek nawiewników i lokalizację wywiewników, obserwując przy tym zmiany rozkładu prędkości powietrza w strefie przebywania ludzi. Stwierdzono, że takie czynniki, jak wysokość położenia wywiewników lub kąat rozwarcia łopatek nawiewników miały w tym przypadku małe znaczenie. Znacznie istotniejszy był wpływ prędkości nawiewania powietrza i rozstawu nawiewników. Wnioski te mogą stanowić wytyczne dla projektantów systemów wentylacyjnych w tego typu halach.

Keywords: **Ventilation; Industrial hall; CFD; Validation; Ventilation opening; Velocity distribution.**

1. INTRODUCTION

Ventilation air diffusion concept is closely connected with the use and specificity of ventilated rooms. In some enclosures, the issue is well recognized. In others the designers signalize difficulties with the attainment of the required parameters in the occupied zone, as well as other problems connected with the airflow. Example of such objects may be large halls, in particular industrials. In such buildings usually mixing ventilation with side wall inlets is applied, these openings

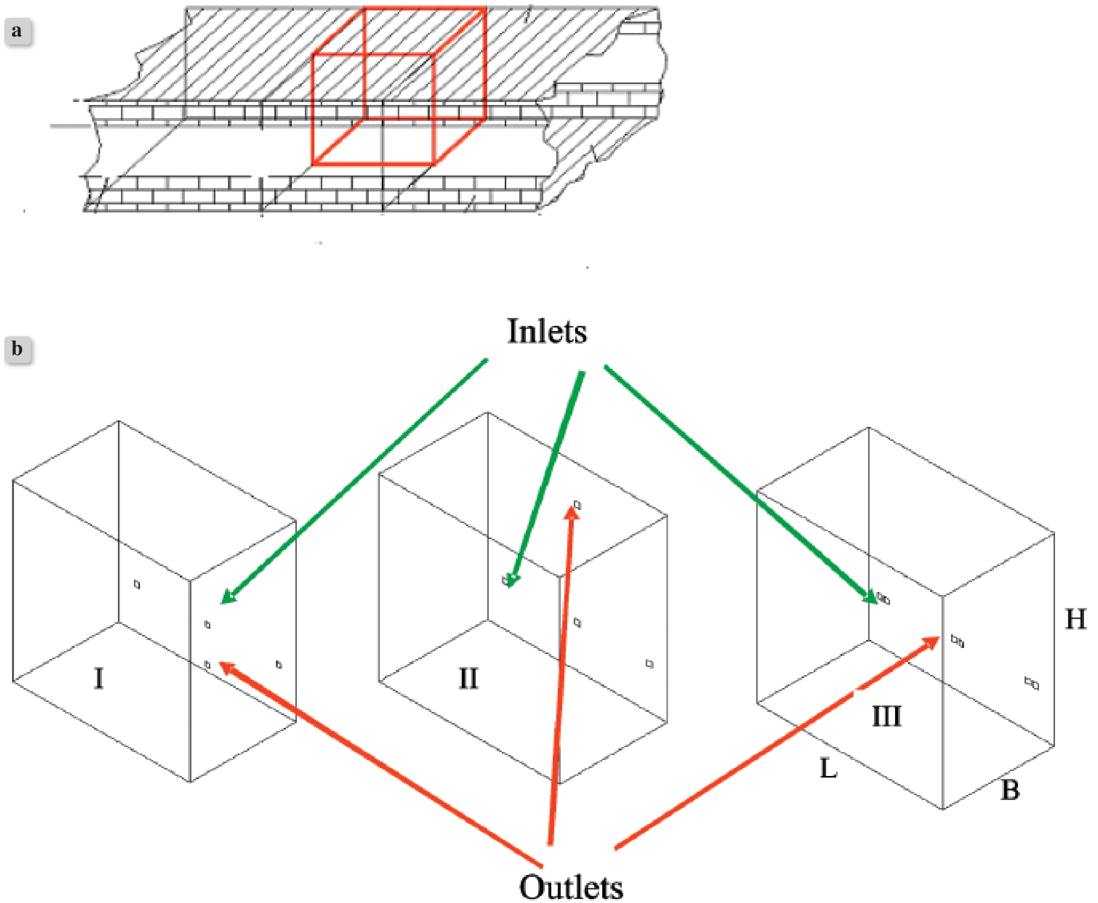

Figure 1.
Scheme of the modelled hall a) view of the real object (recurrent module of the entire structure), b) the numerical model for the various localizations of the outlets

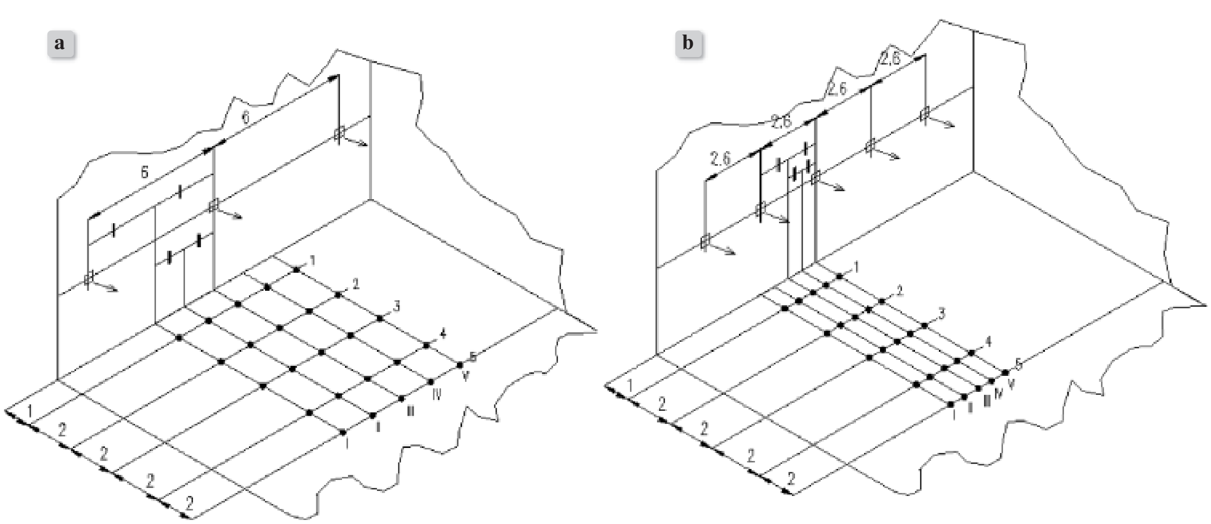

Figure 2.
Measurement points in the physical model of the hall in the horizontal plane on the height y = 1.5 m over the floor for two distances between the inlets S a) 6m, b) 2.6m

being localized above the occupied zone. The supply air is then mixed with the ambient air not all over the hall. In winter in such enclosures the warm air heating is usually applied.

Literature does not provide much information concerning this subject matter. Investigations carried out by Chow et al. [1] concerning a large railway station hall prove that the air change rate is not an adequate coefficient determining the effectiveness of ventilation system in large enclosure. In this case of unsuitable supply air conditions its augmentation not necessarily improving the thermal comfort inside the room. Chow et al. [2] suggest a method of testing the ventilation efficiency in such structure, consisting in the supply of tracer gas into control volumes, but this method did not prove true in case of large halls.

Wong et al. [3] investigated the conditions of thermal comfort by means of various ways of ventilating a large canteen, making use of the CFD technique. Investigations performed within the frame of the Annex 26 IEA [4] dealt with such large enclosure as auditoriums, ice rinks, sport halls etc, the specific character of which differs considerably from the viewpoint of ventilation.

The article presents the influence of various factors related to air diffusion in a large industrial hall on the distribution of air parameters determining the perception of thermal comfort in the occupied zone. The presented study was performed using the CFD method for numerical prediction, and the results were validated using the results of an experiment carried out for physical model of such a hall.

2. CHARACTERISTIC OF THE INVESTIGATED HALL AND ITS NUMERICAL MODEL

For the purpose of numerical calculations a typical industrial hall was chosen with a height of 15 m and a width of 18 m, strictly speaking only its part with dimension $L = 15$ m length, $H = 15$ m height and $B = 9$ m width, assuming it to be representative of the entire structure, being its recurrent module (Fig.1a).

The numerical model of this enclosure, presented in Fig.1b, was developed making use of computer code CFD Flovent 6.1, based on differential equations averaged in time, describing the flow of air and heat. In the numerical modeling the turbulence model k-ε LVEL and standard wall functions were applied.

The air was supplied to the hall through supply openings (with width $b_o = 0.375$ m and height $h_o = 0.275$ m) provided with guide vanes, whose angle of spread α could be adjusted within the range of 0° to 90° at the supply velocity v_o varying from 2.5 to 9.4 m/s. The location of the inlets over the floor (Fig. 1b) at the height of $H_o = 3.5$ m ($H_o/H = 0.23$) was assumed to be constant, but the distance S between them was either 2.6 m ($S/b_{o.} = 6.9$) or 6 m ($S/b_{o.} = 16$). The exhaust openings (Fig. 1b) were positioned at the height $H_e = 0.5$ m ($H_e/H = 0.03$) (I) or 12 m ($H_e/H = 0.8$) (II) over the floor, halfway of the length of the module. The location of the exhaust in vicinity of inlets, i.e. at the height of 3.5 m ($H_e/H = 0.23$) (III) was analyzed, too. Such a positioning of the inlets and outlets in relation to each other is characteristic for air heater unit.

The boundary conditions were preset directly in inlets and outlets. For the purpose of presetting the thermal boundary conditions at the wall in case of non-isothermal conditions heat fluxes were used transferring through the walls. It has been assumed that the heat losses in the hall are thoroughly compensated by the supply air. For the sake of simplification the internal heat gain has not been taken into account.

The calculation concerned isothermal and non-isothermal airflow in steady conditions in 29 selected variants of air diffusion, permitting to investigate the effect of the following factors on the air velocity distribution in the occupied zone:

- the supply air velocity v_o,
- the distance between the inlets S,
- the angle of spread of the guide vanes α in the inlets,
- the height of positioning the outlets h.

3. METHODS OF MEASUREMENTS

The experiment whose results were used to validate the results of numerical calculations was performed in the physical model of a fragment of the hall in the scale of 1:7.5 [5] making use of the technique of physical approximate modeling [4] in steady conditions. The model constructed in the laboratory reflected the shape and structure of the partitions of the hall as well as the surface area of the windows and skylights. The investigations comprised 16 variants selected by means of methods of planning the experiment for isothermal and non-isothermal conditions at various localizations of the exhaust and various conditions of supply air from the viewpoint of its velocity, temperature, the spread of the vanes and spacing of the inlets. For each variant the distribution of velocity in the occupied zone was measures at selected heights above the floor level: y = 1.5 m and y = 3.5 m, using

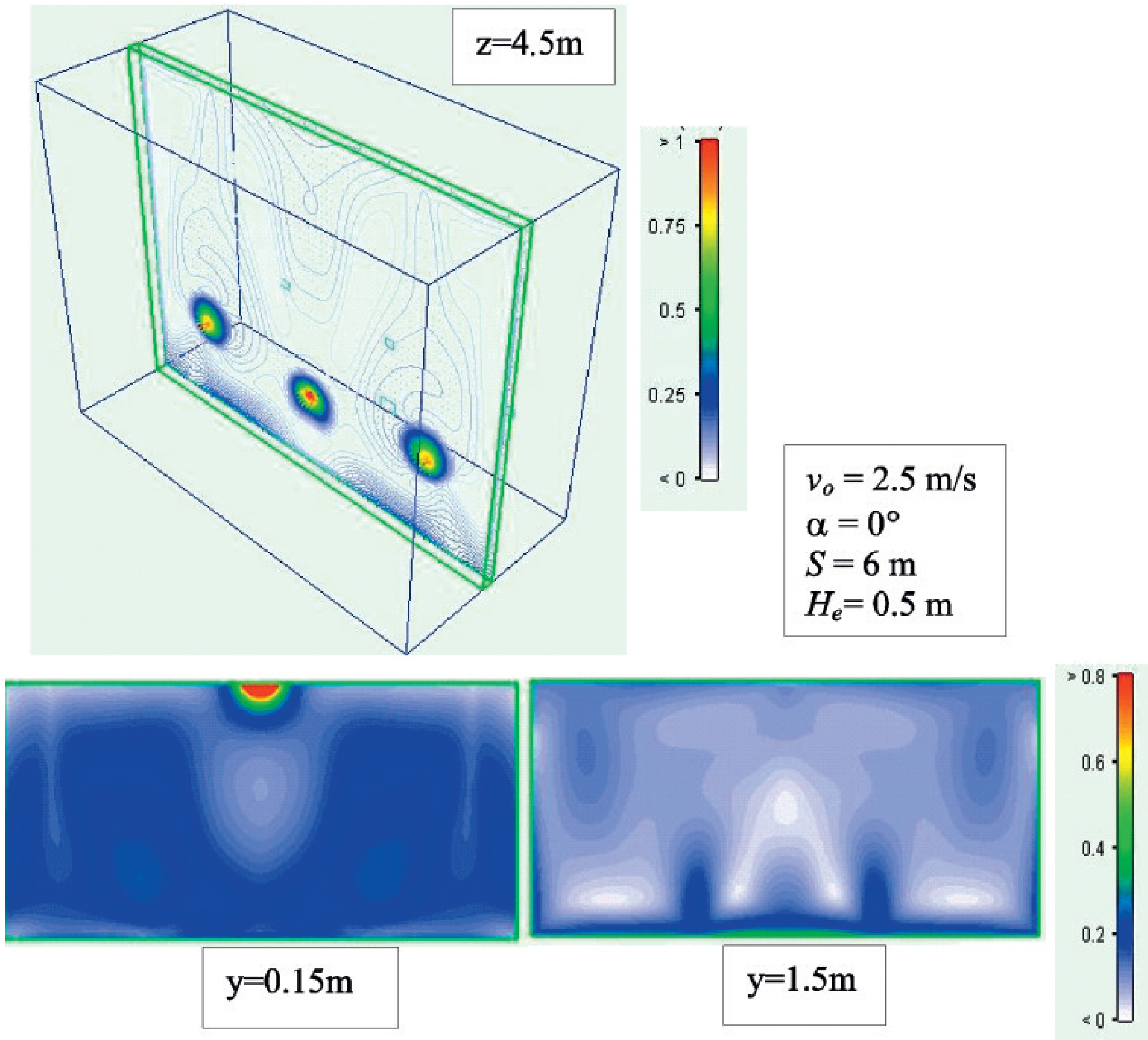

Figure 3.
Predicted velocity distribution in the occupied zone of hall

for this purpose a multichannel spherical thermoanemometer Moreover in case of non-isothermal variants the distribution of temperature was measured by mean of a thermocouple on these same levels as well as in some selected axes at 7 different heights from y = 0.15 m to y = 12 m. Due to considerable consumption of labour the measurement grid was reduced to the space that was assumed to be ventilated by only one supply opening. This was that part of the hall which was separated by vertical planes on both sides of the inlet halfway between the adjacent inlets and the vertical plane in the middle of the width of the hall. On each horizontal plane 25 measuring points were distributed regularly as seen in Fig. 2 concerning two spacings between inlets. The results of these measurements were processed in the way described further on.

4. THE METHOD OF PROCESSING THE RESULTS

The velocities resulting from numerical simulation have been expressed as components of the vector of the velocity averaged in time, based on which the resultant value of the velocity averaged in time, further on simply called “velocity”, can be calculated. A spherical thermoanemometer with multidirectional properties measured the value of the module of the velocity vector averaged in time. Thus, there are two different values. In order to compare them with each

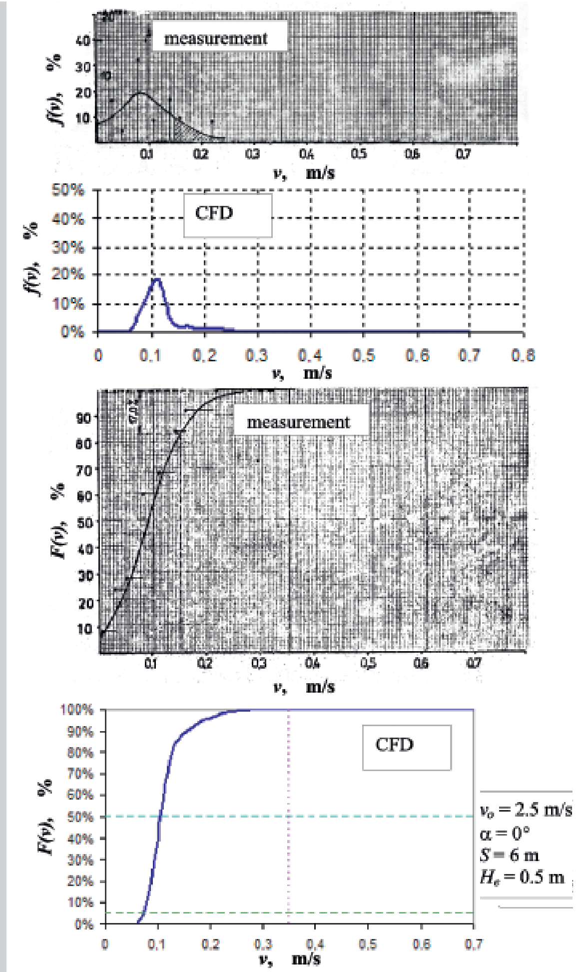

Figure 4.
Comparison of the profiles of frequency function and cumulative distribution of the speed in the occupied zone for y=1.5 m obtained by measurement and from CFD prediction

other, the resultant of components of the velocity averaged in time must be recalculated as a module of the averaged velocity, as has been done applying the method suggested in [6]. For the purpose of simplification, the corrected value will further on be called "speed".

In order to facilitate the comparison of the results of numerical predictions, concerning various cases of air diffusion inside the room and in order to validate these results based on the results of a physical experiment the minimum v_{min}, maximum v_{max} and mean v_m values of the speed were determined for the selected horizontal level in the occupied zone. Then the profiles of the frequency function $f(v)$ were plotted, from which the modal values and corresponding frequencies could be read off, as well as diagrams of the cumulative distribution of this parameter $F(v)$ in the plane, permitting the determination of the median of the velocity distribution. The velocity distribution was characterized by means of two probabilities. P' denotes the probability of the occurrence of speed on this level within the range of value from (v_m – 0.1 m/s) to (v_m + 0.1 m/s). This value provided information about the relative equalization of the speed distribution and was calculated in compliance with the formula:

$$P' = F(v_m + 0.1) - F(v_m - 0.1), \quad (1)$$

The other criterion was the probability P" of the occurrence of the speed within the range from 0.15 m/s to 0.35 m/s, which assumed to be stipulated and admissible because the conditions of thermal comfort are preserved. This parameter is expressed by the formula:

$$P'' = F(0.35) - F(0.15) \quad (2)$$

In the investigations a similar method of assessing, not dealt with in this paper, was applied concerning the temperature distribution.

5. VALIDATION OF THE NUMERICAL CALCULATIONS

The validation of the numerical calculations concerning the occupied zone was presented on the example of a selected variant of the air diffusion in the hall in isothermal conditions, where the air was supplied at velocity v_o = 2.5m/s through 3 supply openings with vanes adjusted at an angle of α = 90°, positioned S = 6 m from each other. The air outlet was situated in the centre of the side wall h = 0.5 m above the floor. The results of calculations of the velocity in the entire hall and in the occupied zone on two levels, obtained by applying a postprocessor of the Flovent

Table 1.
Characteristic values of the speed in the occupied zone based on measurement and numerical calculation CFD

v_0, m/s	P' %	P" %	v_m/v_0 %	v_{max}/v_0 %	v_{min}/v_0 %	median $\%v_0$	modal value v/v_0 %	modal value $f(v)$ %
Measurement	94	17	3.8	10	0	3.8	3.2	18
CFD	97	11	4.4	11.6	2	4.4	4.4	18

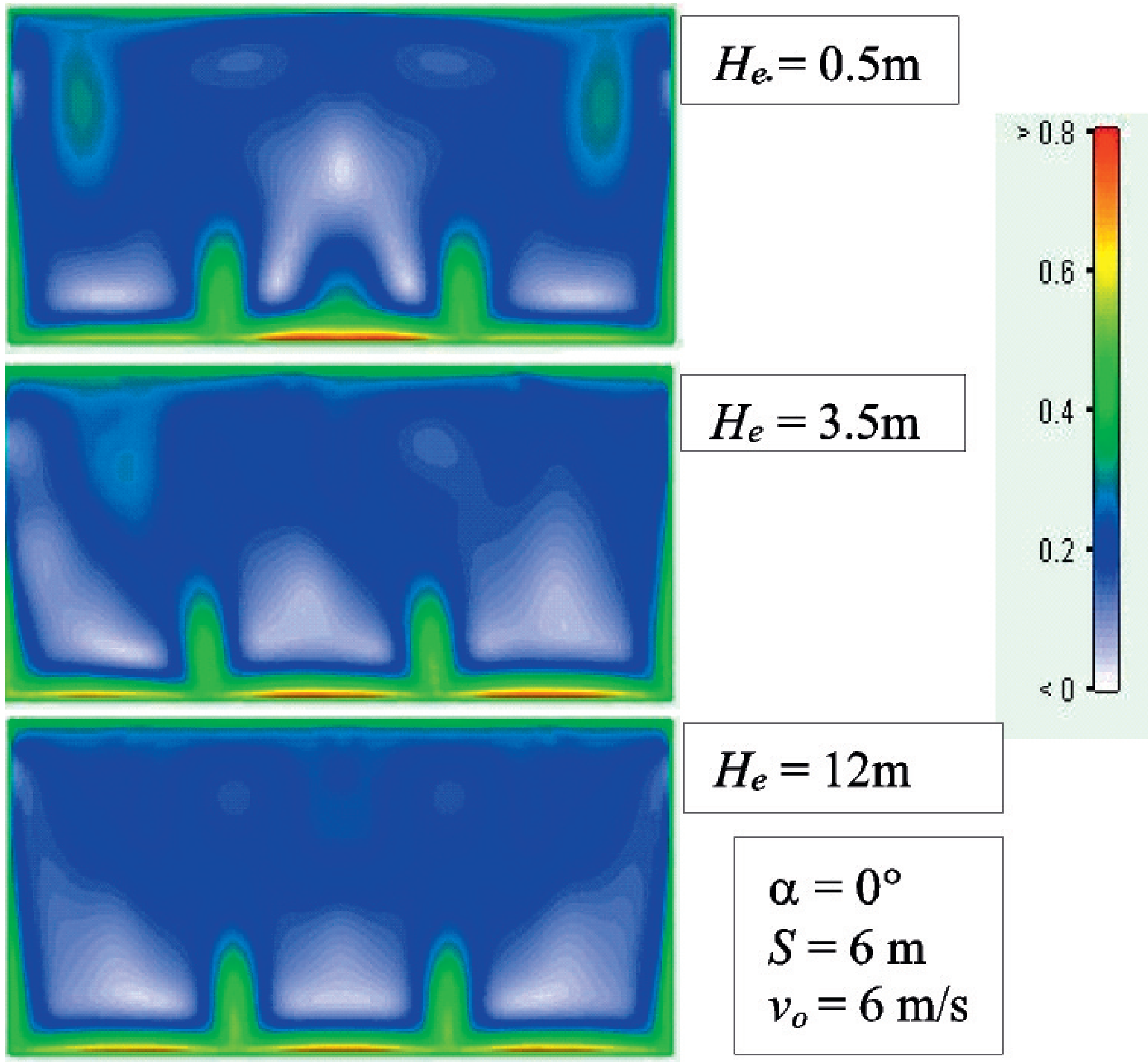

Figure 5.
Maps of the velocity in the occupied zone at the height y=1.5 m for various heights of the outlets localization

code, are to be seen in Fig. 3

The results of numerical predictions were compared with the experimental results making use of the previously presented method of describing and assessing the distribution of the air parameters. The comparison comprised the calculated and measured value of frequency function and cumulative distribution for the plane y = 1.5 m (Fig. 4). The diagrams were similar in both modes of modeling. The compared parameters characterizing the speed distribution have been gathered in the Table 1.

In the analyzed conditions the range of speeds, determined basedon the results of numerical simulation was contained within the limits from v_{min} = 0.05 m/s a v_{max} = 0.29 m/s. The measured values of the velocities ranged from 0 m/s to 0.25 m/s. Probability P' amounted to 97% and 94%, respectively. Probability P" amounted according to the prediction to 11%, whereas according to measurements it was 17%. The calculated mean value of the speed was equal 0,11 m/s, whereas the measured value amount to 0.095 m/s. The median of the velocity was equal to the mean velocities of both cases. The modal value of the speed was 3.2% of supply velocity in case of measurement and 4.4% in case of calculations. Their corresponding frequencies attained in both cases the value of 18%.

Table 2.
Characteristic values of the speed in the occupied zone for various heights of the outlets localization

h *m*	P' %	P'' %	v_{mr}/v_0 %	v_{max}/v_0 %	v_{min}/v_0 %	median $\%v_0$	modal value v/v_0 %	modal value $f(v)$ %
0.5	90	88	4.5	10.7	2.8	4.4	4.5	10
3.5	91	90	4.3	9.5	2.3	4.3	4.2	12
12	92	91	4.3	9.5	2.8	4.2	4.3	12%

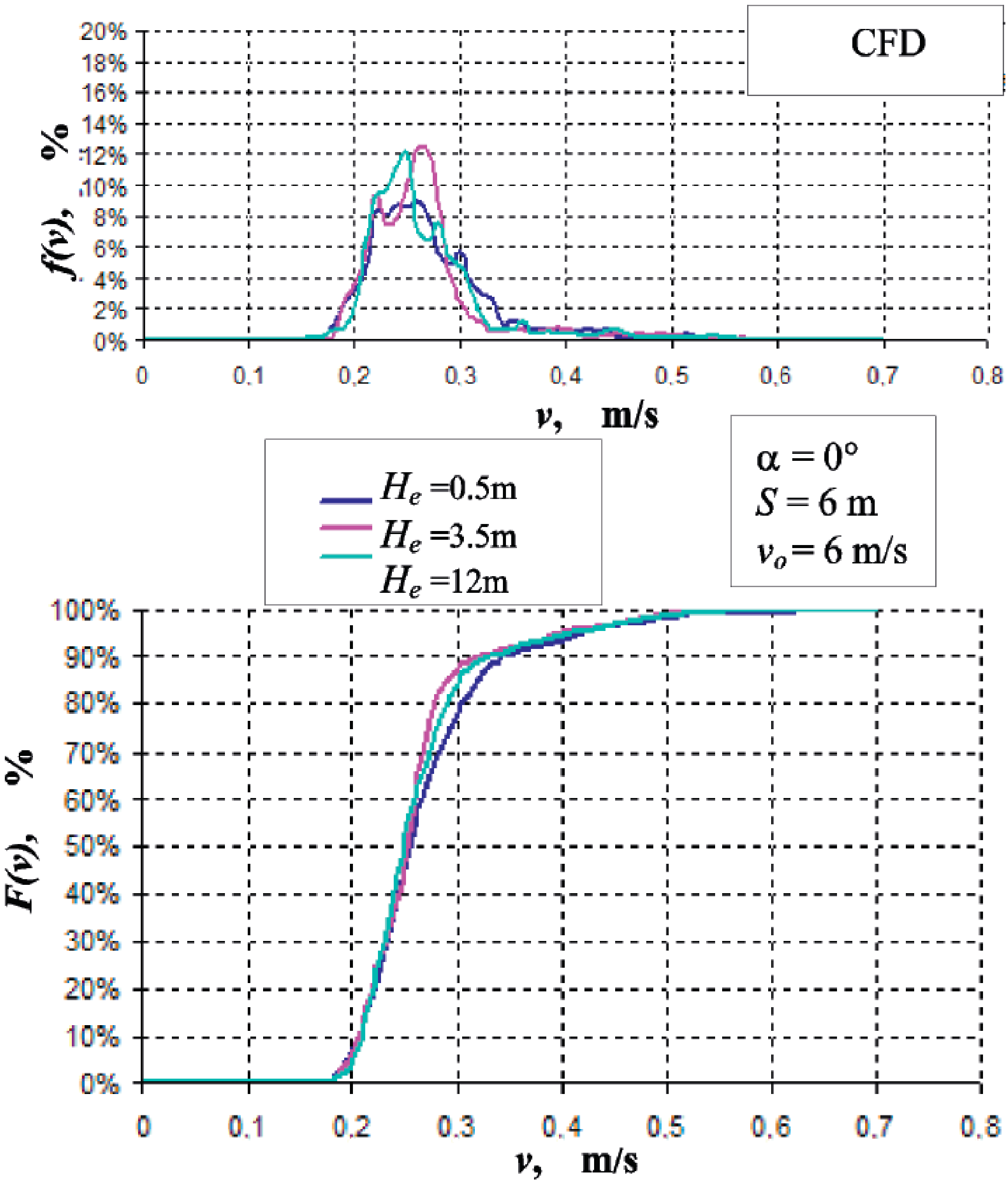

Figure 6.
Comparison of the profiles of frequency function and cumulative distribution of speed in the occupied zone for y=1.5 m for various heights of the outlets localization

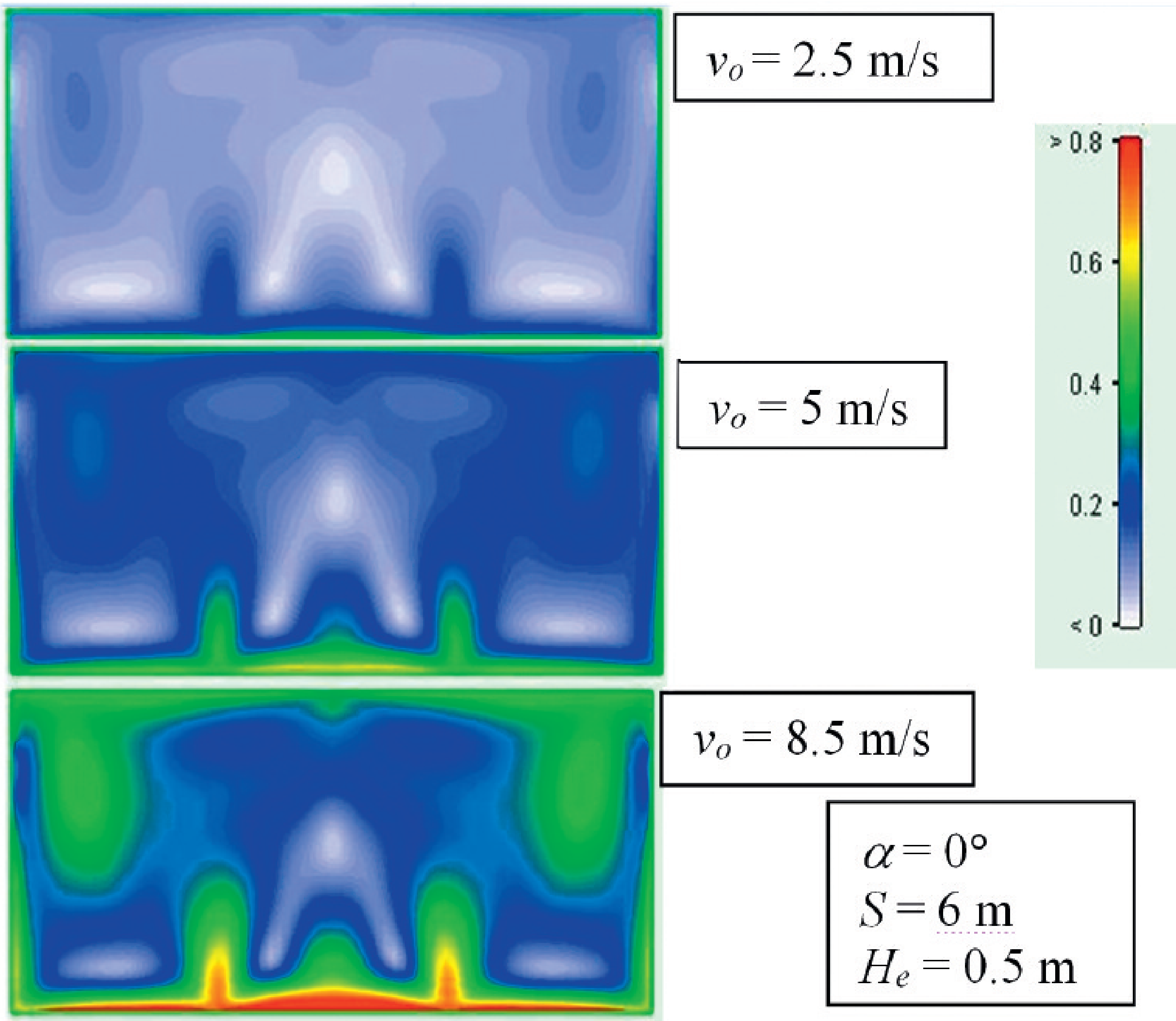

Figure 7.
Maps of the velocity in the occupied zone at the height y=1.5 m for various values of supply air velocity

Table 3.
Characteristic values of the speed in the occupied zone for various values of supply air velocity

v_0 m/s	P' %	P" %	v_{mr}/v_0 %	v_{max}/v_0 %	v_{min}/v_0 %	median $\%v_0$	modal value	
							v/v_0 %	$f(v)$ %
2.5	98	8	4.4	10.8	2.8	4.1	4	22
5.0	98	93	4.6	10.8	2.8	4.4	4.6	10
8.5	85	41	4.8	10.7	2.8	4.3	4.4	7.9

Based on these comparisons and on the results concerning other variants presented in [7] we may conclude that by means of numerical prediction CFD the distribution of speed in the occupied zone of the investigated hall has been simulated rather exactly. Several observed discrepancies may be justified by other conditionings concerning the applied methods of measurements and calculation. In calculation the assumed discretization grid permitted to obtain about 3400 nodes in one plane within the range of the occupied zone. Physical modeling was restricted to merely 25 measuring points in this plane.

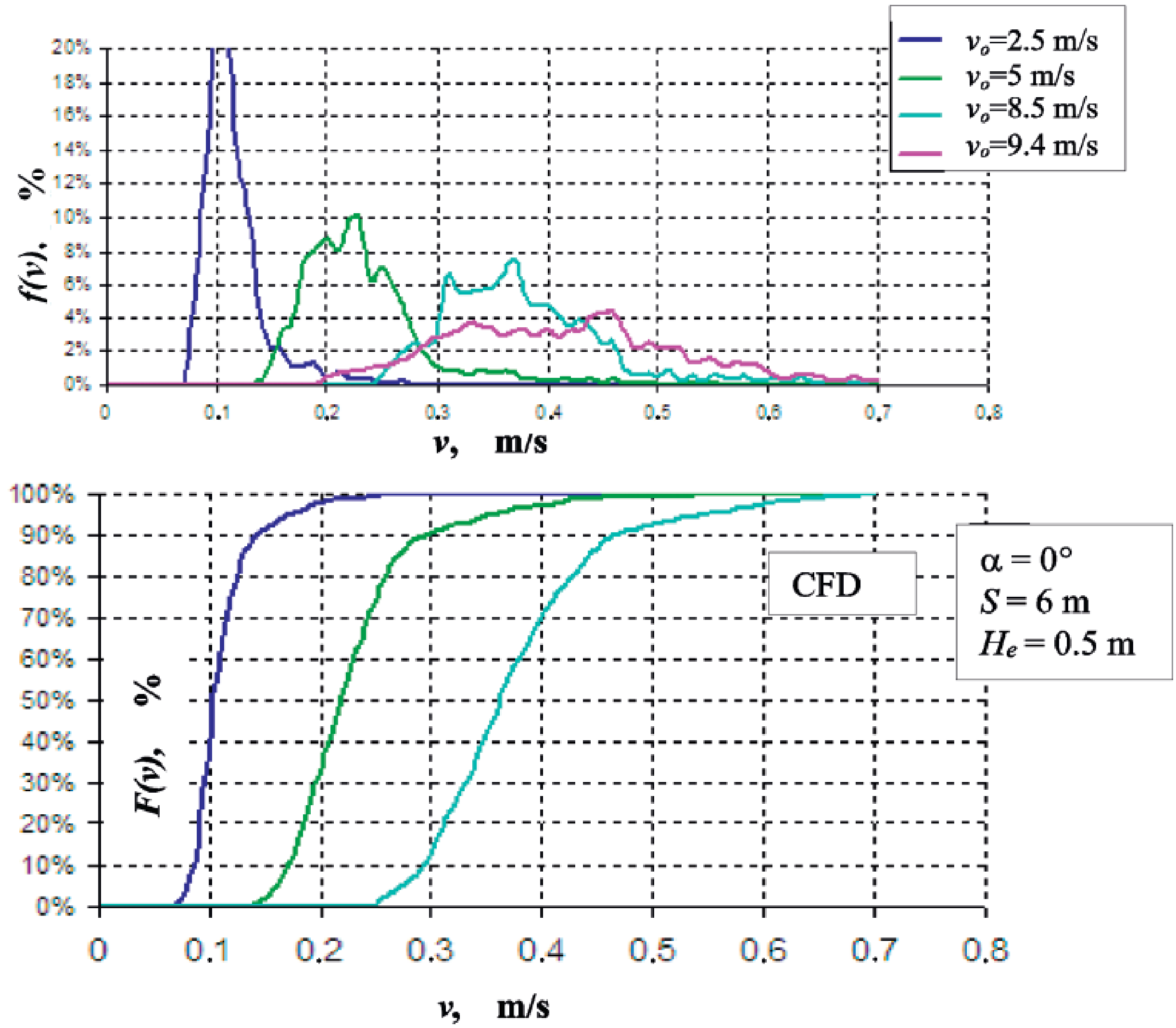

Figure 8.
Comparison of the profiles of frequency function and cumulative distribution of the speed in the occupied zone for y=1.5 m for various values of supply air velocity

6. RESULTS AND DISCUSSION

In compliance with the aims of the presented investigations the influence of various factors connected with the supply and exhaust of air on the speed distribution in occupied zone at the height y = 1.5 m was analyzed based on the results of numerical calculations.

6.1 The influence of the localization of outlets

For the conditions of the air diffusion presented in Fig. 5 the localization and number of exhaust openings was varied; these outlets were positioned as follows:

– a single outlet in the centre of the side wall near the floor at the height H_e of 0.5 m,
– a single outlet in the centre of the side wall at the top of hall at the height of 12 m,
– 3 outlets simulating the exhausts in the air-heater units, positioned in the vicinity of the inlets at the height H_e of 3.5 m.

Map presenting speed concerning all these cases have been gathered in Fig. 5. Quantitative comparisons did not indicate any essential influence of these variations on the distribution of this parameter.

Based on the specification presented in Table 2 the mean, maximum and minimum values of the speed in all the three cases were compared. The mean speed amounted to 0.27m/s or 0.26 m/s, the maximum val-

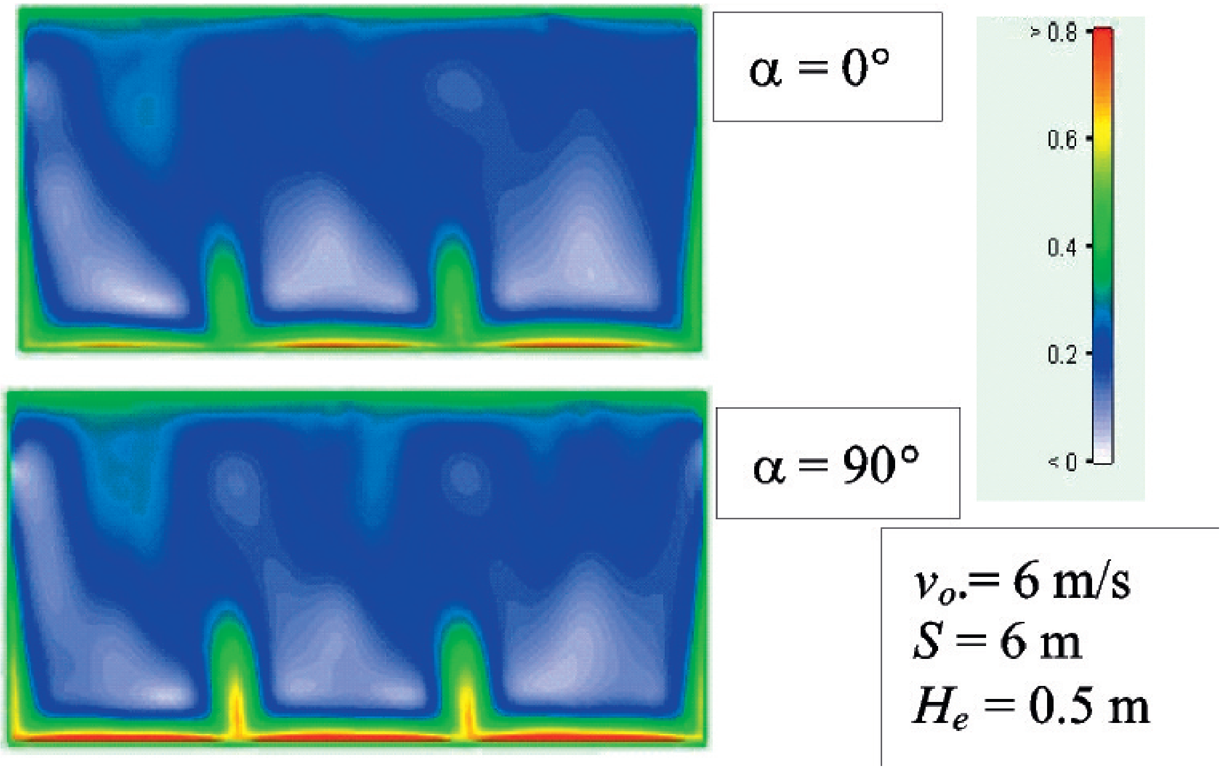

Figure 9.
Maps of the velocity in the occupied zone at the height y=1.5 m for various angles of the vanes in the inlets

Table 4.
Characteristic values of the speed in the occupied zone for various angles of the vanes in the inlet

α	P' %	P" %	v_{mr}/v_0 %	v_{max}/v_0 %	v_{min}/v_0 %	median $\%v_0$	modal value v/v_0 %	modal value $f(v)$ %
0°	90	91	4.3	9.5	2.3	4.2	4.2	12
90°	91	92	4.2	10.5	1.8	4.2	3.8	10

ues were equal in two cases, amounting to 0.57 m/s and only in case of outlet at the height of 0.5 m the maximum speed reached the value of 0.64 m/s. The minimum speed oscillated within the range of 0.14 m/s to 0.17 m/s. For each case the probabilities P' and P" were compared, values of which were contained in the limits from 88% to 91% and from 90% to 92%.

Comparison of the distributions of the frequency function of speed (Fig.6) did not reveal any differences in their shape. The frequency of occurrence at the peak point was 12%, except the variant for which the air was exhausted at the bottom. In this latter case the frequency of occurrence was somewhat lower, amounting only to about 9%. In all the cases the modal values were contained in the range from 0.24 m/s to 0.26 m/s. The cumulative distribution of the speed displayed in all these case nearly the same shape, mostly coinciding with the each other, similarly as the values of median, amounting to about 0.26 m/s.

Thus it may be said that the situation of the exhaust openings affected the airflow in the hall only locally without influencing the distribution of the air speed in the occupied zone.

6.2 The influence of the supply velocity

Concerning the conditions of air diffusion, presented in Fig. 7 the supply air velocity was varied within the range from 2.5 to 9.4 m/s and the influence of such a variation on the velocity distribution in the occupied zone was the subject of investigations.

The quantitative comparison based on the maps of velocity is presented in Fig. 7, from which it results that the level of the range of velocity in the occupied zone increases with the growing supply velocity. This has also been confirmed by the qualitative analysis

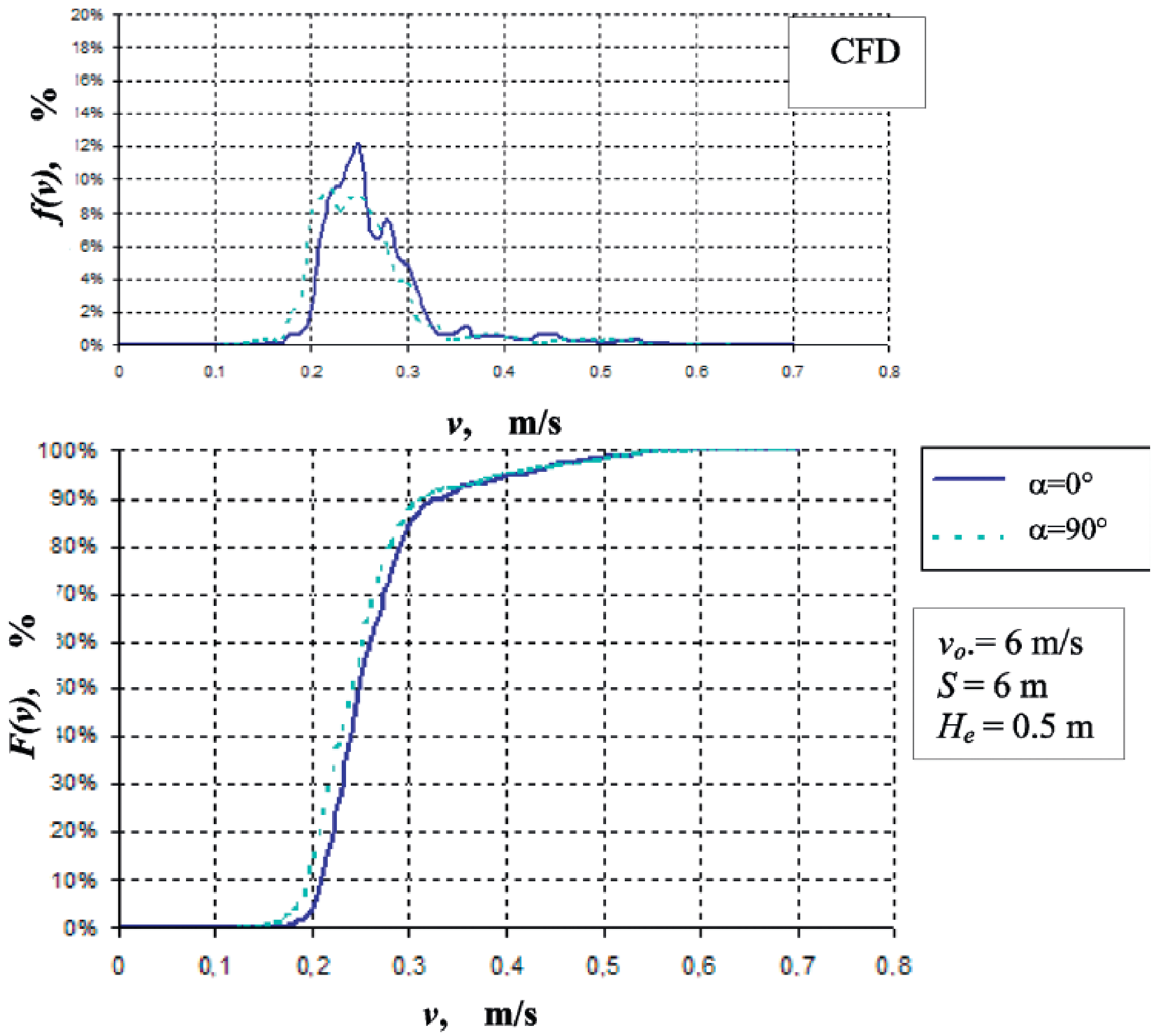

Figure 10.
Comparison of the profiles of frequency function and cumulative distribution of the speed in the occupied zone for y=1.5 for various angles of vanes in the inlets

presented in the Table 3, indicating that the growth of the mean speed value was proportional to the supply velocity amounting to 4.4-4.8 v_o. Quite similar was the case with the minimum and maximum speed, which amounted respectively to 2.5% and 10.7-10.8%. Fig. 8 shows a similar relation between the median and the modal value of this parameter. The frequency of the occurrence of the modal value abated with the increasing supply air velocity. The increase of v_o to above 5 m/s involved a decrease of the share of the surface area P' which proves a deterioration of the equalization of the air speed.

6.3. The influence of the angle of spread of the guide vanes in the inlets

Investigation concerning the influence of the spread of the vanes were carried out for the supply opening producing a parallel jet (α = 0°) and also a diffused jet (α = 90°).

The results of the calculations, presented in the Figs 9 and 10, as well as those contained in Table 4 do not indicate any essential differences between these two modes of air supplying into the hall. Merely an expansion of the range of speed from 2.3 to 9.5% v_o is to be observed in case of the parallel jet, and to 1.8-10.5% v_o in case of the diffused jet.

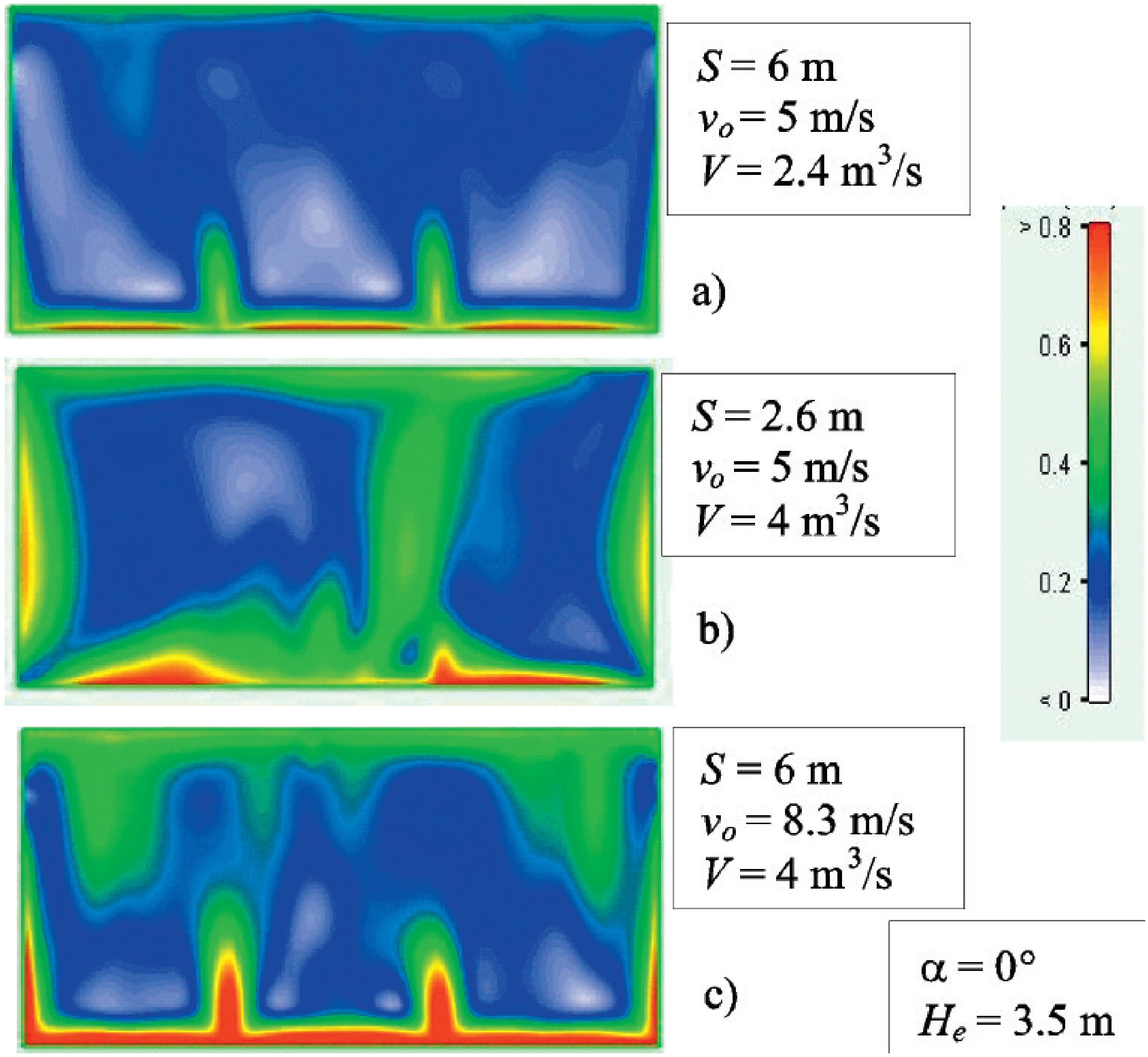

Figure 11.
Maps of the velocity in the occupied zone at the height y=1.5 m for various distances between the inlets maintaining a constant supply air velocity (a, b) or supply air volume rate (b, c)

Table 5.
Characteristic values of the speed in the occupied zone for various distances of the inlets maintaining a constant supply air velocity or the supply air volume rate

S *m*	V_0 *m/s*	P' %	P" %	v_{mr}/v_0 %	v_{max}/v_0 %	v_{min}/v_0 %	median $\%v_0$	modal value	
								v/v_0 %	$f(v)$ %
6	5	92	92	5	12.6	2.2	4.6	5	10
2.6	5	65	51	7.6	15.8	3.6	7	6.2	7
6	8.5	86	40	4.9	11.7	2.3	4.3	3.9	8

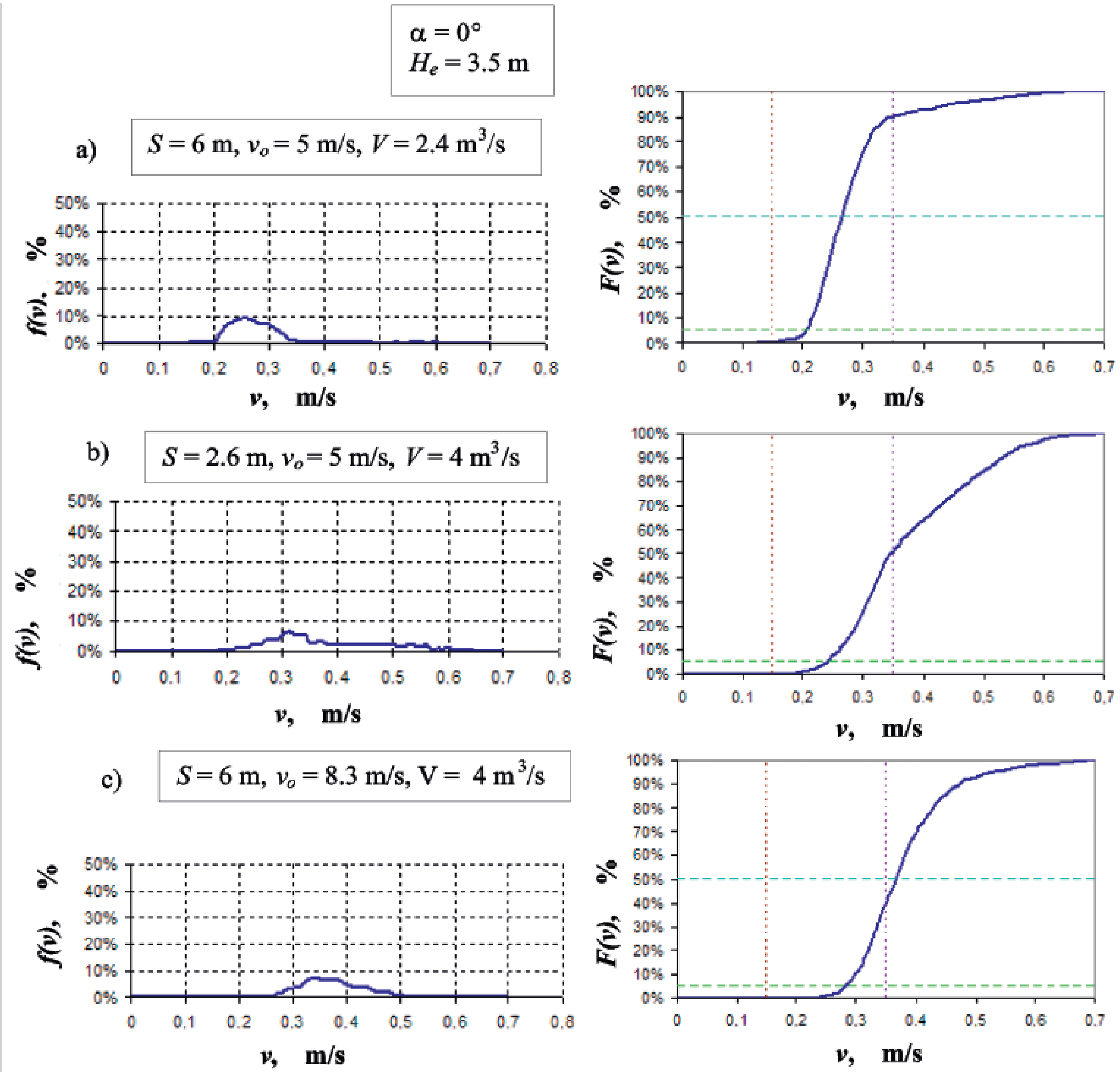

Figure 12.
Comparison of the profiles of frequency function and cumulative distribution of speed in the occupied zone for y=1.5 m for various distances of inlets maintaining a constant supply air velocity (a, b) or supply air volume rate (b, c)

6.4. The influence of the spacing between the inlets
The influence of the spacing between the inlets on the velocity distribution was tested, comparing the respective variants with each other in cases of the supply air velocity or air volume flow rate being constant. Two different spacings were analyzed, $S = 6$ m and $S = 2.6$ m, the other conditions being unchanged, as shown in Fig. 11.

Scanning the map of velocity permitted to discern quantitative differences between the respective pairs of compared results of calculations (a and b) and (b and c).

Based on the qualitative analysis and maintaining a constant supply air velocity it has been found that supplying air through a smaller number of inlets situated farther away from each other resulted in a drop of the maximum, minimum and mean values of the speed in the occupied zone, and also the median and modal value of the spatial distribution of this parameter (Table 5). Simultaneously, the value of the frequency corresponding to the modal value decreased, which is also to be seen in Fig. 12a) compared with 12b). The values of the functions P' and P", however, increased respectively by 29% and 37%, proving an

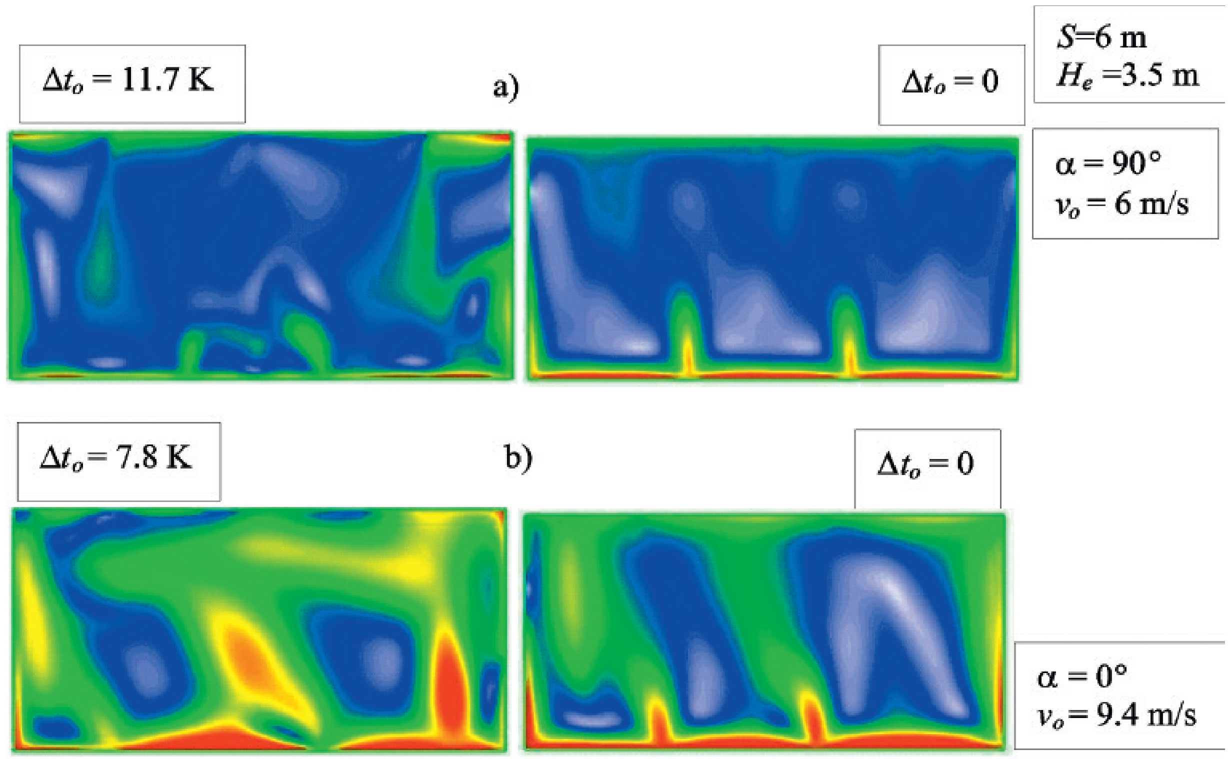

Figure 13.
Maps of the velocity in the occupied zone at the height y=1.5 m for isothermal and nonisothermal supply air jet

Table 6.
The influence of the nonisothermal air jet on the characteristic values of the average velocity in test large hall

t °C	v_0 m/s	P' %	P" %	v_{mr}/v_0 %	v_{max}/v_0 %	v_{min}/v_0 %	median $\%v_0$	modal value	
								v/v_0 %	$f(v)$ %
28	6	91	88	4.7	10.3	2.5	4.4	4.2	9.7
16	6	90	90	4.7	12.1	1.7	4.2	4.2	9
23.8	9.4	54	18	5.3	11. 2	2. 7	4.7	5.3	3
16	9.4	63	33	4. 5	10.2	2.0	4.4	4.8	4.2

improvement of the equalization of the speed and an increment of the surface area on which the requirements of the thermal comfort have been satisfied.

The discussion concerning the respective results, by preservation of air volume flow rate supplied to the room, permitted to ascertain that the increase of the distances is accompanied by an increase of the characteristic value of the speed, the median and modal values, similarly as before. The probability P' changed by 31%. Only probability P" changed less, being reduced by 11%.

Thus, it may be expected that increased distances between the supply air openings and the reduction of their number will influence favourably the conditions in the occupied zone, provided the supply air velocity and hence also air volume flow rate will be chosen properly.

6.5. The influence of the non-isothermal supply jet

The influence of the supplied warm jet on the velocity distribution in the occupied zone was assessed by comparing non-isothermal variants with their corresponding cases of supplying isothermal jets, as shown in Fig. 13 concerning two selected pairs of variants differing from each other with respect to temperature, supply air velocity and the kind of the generated jet. The qualitative analysis did not in either case reveal any essential changes on the velocity maps.

This has been proved in Table 6, displaying the invariability of the mean speed by the supplying diffused jet and slight increase of this parameter, if compared with the effect of the parallel supply jet. Also the range of speed did not change much.

The frequency function of the speed (Fig. 14) con-

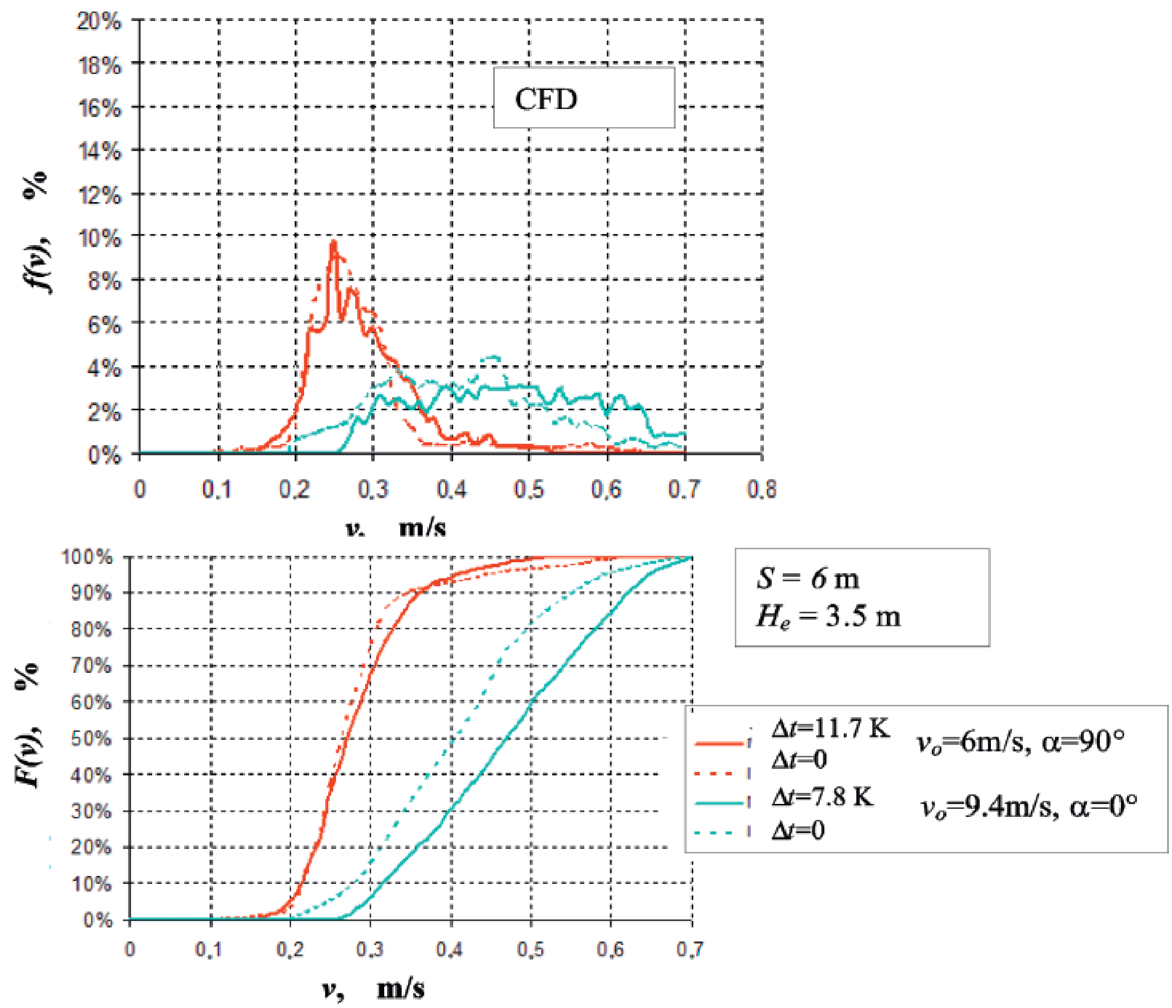

Figure 14.
Comparison of the profiles of frequency function and cumulative distribution of speed in the occupied zone for y=1.5 m for isothermal and nonisothermal supply air jet

cerning the comparable pairs of results had a similar shape and the modal value. The curves of the cumulative function were also similar, at the lower supply velocity they were in both cases coincident. Similar results were obtained from the analyses at the spacing of the inlets S = 6 m, not dealt with in this paper [7].

Comparing the values of the probability P', a considerable drop of its value is to be noticed in case of non-isothermal supply at greater velocity. It was similar with the probability P".

Summing up the qualitative and quantitative assessment it may be said that the non-isothermal supply jet in the considered range of the air temperature in ventilated rooms did not affect considerably the temperature distribution in the occupied zone. Therefore, the results as well as the conclusion concerning isothermal flows may also be applied in the design of the air heating of the halls.

7. CONCLUSIONS

Basing on the performed validation of numerical prediction in the investigated hall it has been found that the results of these calculations may find application in the assessment of the velocity distribution as one of the parameters characterizing the thermal comfort in the occupied zone.

The presented investigation permitted to determine the influence of the conditions connected with the supply and exhaust of air in the hall on the velocity distribution in the occupied zone. It has been found that such factors as height of the positioning of the outlets or the spread of the vanes are in this case of less importance. Much more important must be assigned to the supply air velocity and spacing of the inlets.

As the temperature of the supply air, within the range applied in the ventilation, does not influence its velocity in the occupied zone, the results and consequent conclusions concerning isothermal flows may hold true also of the air heating of the hall.

The conclusion resulting from these investigations may constitute guidelines for designers of ventilation systems in choice of the proper way of distributing the air in large halls.

The suggested method of assessing the thermal comfort by means of numerical simulation CFD may find application not only in industrial halls, but also in other large enclosures, such as supermarkets, service halls and railway station.

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