Numerical Modeling of Comfort Parameters for Spectators in Large Concert Halls

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Abstract. The numerical modelling of spectators and performers’ comfort in large concert halls was considered. The research shows that numerical modeling of air velocity and temperature helps to make a justified choice of technical solutions for ventilation and air conditioning systems and to examine their operation under extreme mode of service as well.

1. Introduction

While designing new modern buildings and restoring unique old concert halls great attention is being paid to the conditions for spectators [1-7] and the demands for appropriate acoustic parameters.

According to the Russian Federation standards, comfortable conditions are as follows: ambient air temperature 23...25 °C, its velocity is up to 0.3 m/s (desirably about 0.2 m/s). It should be noted that local temperature difference of the height of spectator zone i.e. in the range of 0.1 to 1.5 m, should not be more than 3 °C, and air velocity change should not exceed 0.1 m/s (50 %). At the same time in summer it is desirable that the temperature inside a hall should approach the upper limit and in winter – to the lower one. Seats distribution at different levels (stalls, balconies, etc) and total height of halls up to 20 m and higher add to the complexity for the estimation and modelling.

Nowadays solution for such tasks on the stage of building designing by computational gas dynamic (CFD) methods has been widely distributed [8-15]. Growing performance of computation machines and improvement of computational algorithms make it possible to discretize the halls with large volume without precision loss. Numerical models including from 10 to 100 million elements are widely used for test tasks solutions and in applicative calculations [12].

Speaking about classification, it should be said that there are two main research directions: estimation of comfort conditions for closed [11-15] and open places [8-10]. Meanwhile those very places can contain specific features which can significantly influence the calculation procedure. Dealing with closed places one should consider researches [11-12] where the calculations were carried out for hockey pitch, design of a swimming pool [15], or the factors of a theatre located in tropic zone were taking into account [14].

Thus it is clear that while designing concert halls and other culture centres CFD-modelling can significantly reduce duration of the work and increase the quality of ventilation and conditioning processes according to the modern standards.

In this study the application of CFD calculations during the construction of a Philharmonic hall is shown (Fig.1) Software package ANSYS-CFX was used as modelling instrument.
Figure 1. Solid-state model of Philharmonic Hall.

2. Numerical model

The solution was made on the basis of numerical model consisting of differential continuity equations, Reynolds equation system, equation of state, energy for air inside the room under investigation, boundary conditions closing this system and equations describing turbulence model [16].

The accepted assumptions:
- stationary problem;
- working body – gas (air) is considered to be Newtonian and viscous;
- the problem is solved in 3D position, the flow is turbulent.

Thus equation system is as follows:

Continuity equation:

\[ \frac{\partial \rho U_i}{\partial x_j} = 0. \]

Momentum equations:

\[ \frac{\partial \rho U_i U_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu + \mu_t \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3} \frac{\partial U_k}{\partial x_k} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij} \right) + g_i \rho. \]

Energy equations:

\[ \frac{\partial \rho U_i T}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_t} \right) \frac{\partial T}{\partial x_j}, \]

where \( x_i \) is the Cartesian coordinate in the i-direction, \( U_i \) is the flow velocity in the i-direction, \( \rho \) is the density of air, \( T \) is the temperature, \( P \) is the pressure, \( \mu \) is the molecular viscosity of the air and \( g_i \) is the acceleration of gravity, \( \mu_t \) is the eddy viscosity, \( \delta_{ij} \) is the Kronecker delta and \( k \) is the average turbulent kinetic energy per unit mass, \( \sigma_t = 0.9 \) is the turbulent Schmidt number for \( T \).

In the present work, turbulence is modelled with the shear stress transport (SST) model [17]. This turbulence model uses a blending function to combine advantages of the \( k-\varepsilon \) in the free stream...
region and the \( k - \omega \) models in the near-wall region. The turbulent eddy viscosity is computed from the turbulent kinetic energy and turbulent frequency \( \omega \):

\[
\mu_t = \rho \frac{k}{\omega}.
\]

In our case the density variation is driven only by small temperature variations, it means that the Boussinesq model is completely enough for calculations. In this model, a constant reference density is used for all terms other than the buoyancy source term. The buoyancy source term is approximated as:

\[
\rho - \rho_{ref} = -\rho_{ref} \beta (T - T_{ref}),
\]

where \( \rho_{ref} \) is the reference density, \( T_{ref} \) is the buoyancy reference temperature, \( \beta \) is the thermal expansivity:

\[
\beta = \frac{1}{\rho} \left. \frac{\partial \rho}{\partial T} \right|_p
\]

3. The modelling results

As our experience shows it is suitable to divide modelling into 2 stages: at first to model thoroughly the spectators area and to evaluate the validity of the accepted technical solutions on location, types of devices and volumes of fresh air blown inside.

On the balcony of the concert hall the location scheme of air blowing diffusers in the steps was considered. The results of velocity and temperature fields modelling with air supply of 43 m\(^3\)/h per one spectator and their heat release of 72 W are shown in Fig.2, 3. As one can see from the results obtained on the last row the level of comfort is not acceptable (the speed exceeds 0.3 m/s, temperature is more than +25 °С). Afterwards it was decided to supply additional air into the last step (Fig. 4, 5). Now we can see that the comfort conditions are almost achieved.

Figure 2. Location of diffusers supplying air and speed distribution as scalars on the balcony, m/s.
Figure 3. Temperature distribution on the balcony, °C.

Figure 4. Location of air supplying diffusers and velocity distribution as scalars on the balcony in the presence of an additional diffuser, m/s.

Figure 5. Temperature distribution on the balcony in the presence of an additional diffuser, °C.
The next stage is modelling in the total volume of the hall for determining the location of air removal points and their volumes. Also it is often required to check the hall for extreme conditions of maintenance: the increased number of spectators, reduced volumes of air supply, etc. It should be noted that the model of the place must be detailed and thoroughly calculated. Figures 6, 7 represent temperature field of the concert hall under nominal air supply (89 900 m$^3$/h) and 50 % (59 900 m$^3$/h) reduced air flow. At nominal flow the temperature almost everywhere does not exceed 26 °C. However if the flow is reduced by 50 % the temperature becomes more than 26 °C for approximately 60 % of audience creating uncomfortable conditions. It is inadmissible in a concert hall.

Figure 6. Temperature distribution on the balcony in the presence of an additional diffuser, °C.

Figure 7. Temperature distribution in cross-section +1 m from the middle of the hall under nominal flow, °C.
4. Conclusion
Numerous researches into numerical modelling of unique concert halls with modern hydrodynamic and heat exchange software packages lead to the conclusion that this approach gives us an opportunity to carry out scientific and engineering researches into audience comfort and accept proper technical solutions on ventilation and conditioning systems [1, 2].

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Figure 8. Temperature distribution in cross-section +1 m from the middle of the hall under 50% reduced flow, °C.
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