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NUMERICAL SIMULATION OF A COOL AIR FLOW INSIDE THE FIRST PART OF 06T-CAGLIARI TRAM PASSENGER SPACE

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Abstract. *This paper deals with application of CFD methods contained in professional software package Fluent on a numerical solution of engineering practice problem which consists in numerical simulations of a cool air flow inside the first part of 06T-Cagliari tram passenger space. The air-conditioner exhausts a cool air into the internal passenger space via outlet gaps of longitudinal air channels. A cool air is assumed incompressible according to the Boussinesq approximation and its flow inside the closed passenger space is solved as an unsteady natural convection problem. The numerical simulations are realized for two computational models – without and with passengers aboard. Computed values of the air velocity and temperature are compared with recommended limiting values published in available relevant standards.*

1 INTRODUCTION

As a result of arising traffic in larger cities, increasing number of citizens carry themselves with public traffic vehicles. Therefore, increasing requirements are put on thermal and general comfort of passengers in public traffic vehicles. Air-conditioning system considerably contributes to the comfort of the passengers. In agreement with this fact, ŠKODA TRANSPORTATION has developed and produces a five-part wholly air-conditioned tram 06T-Cagliari, see Figure 1.

Suggested rail vehicle air-conditioning system consists of seven independent air-conditioners for air cooling in the passenger space and two air-conditioners for driver's cabins, all designed to be fixed on the tram top[8]. The first part of the tram has one independent air-conditioner with the specified cool air quantity delivery, which gives $850\ m^3/h$. Since the driver's cabin is separated from the passenger space by a wall and has its own individual air-conditioning system, the first part is considered without the cabin in computations.

The contribution follows the problem of numerical simulation of a cool air flow in air channels of the first part of 06T-Cagliari tram, further described in paper[5], where a simple geometric arrangement is suggested for elimination of local non-uniformities in velocity distribution along the outlet gaps through which cool air exhausts into passenger space. The aim of this contribution is to realize numerical simulations of a cool air flow inside the tram passenger space and to compare obtained values of velocity and temperature with recommended limits mentioned in the available relevant standard[6].

Figure 1: The 06T-Cagliari tram

2 STATEMENT OF A PROBLEM

Being exhausted from outlet gaps of longitudinal air channels of the tram air-conditioning system, a cool air enters the internal passenger space. Subsequently, the cool air is spread in the tram interior where heat exchange occurs. Then, in case of the door and all the windows are being closed, the warmed air is sucked in the rectangular orifice of the air-conditioner at the top of the tram passenger space. Two computational models – without and with passengers aboard – are considered for the numerical simulations. According to the available standard[6], 4 standing persons per square meter of the floor area have been modeled.

2.1 Computational domain

The internal passenger space of the first part of 06T-Cagliari tram, represents a bounded computational domain $\Omega \subset R^3$ with a boundary $\partial\Omega = \partial\Omega_I \cup \partial\Omega_O \cup \partial\Omega_S \cup \partial\Omega_W$, illustrated in Figure 2. $\partial\Omega_I$ is the inlet to the internal passenger space (all outlet gaps of longitudinal air channels of the air-conditioning system), $\partial\Omega_O$ is the outlet from the internal passenger space (the rectangular inlet to the air-conditioner at the top of the passenger space). $\partial\Omega_S$ is the vertical boundary of the computational domain, separating the tram first part from the rest, where symmetry boundary condition is applied and $\partial\Omega_W$ are the solid walls (the rest part of the computational domain boundary). The computational domain was created in Gambit preprocessor according to the company design documentation[8]. The tram motion direction is given by the positive *x* axis of the defined Cartesian coordinate system, see Figure 2. The computational domain respects in detail the real tram interior, including passenger seats and hand rails. In the computational domain, 12 sitting and 20 random standing passengers aboard are simply modeled, see Figure 2 (right), to satisfy the normative test number of passengers aboard[6], which prescribes 4 standing persons per square meter.

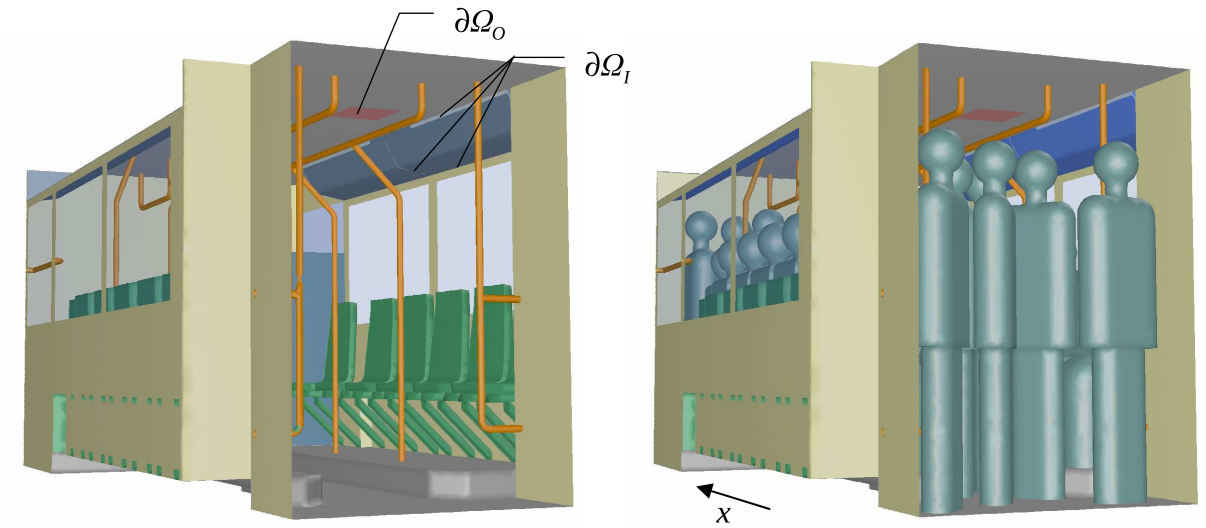


Figure 2: Computational domain – interior of the first part of 06T-Cagliari tram without (left) and with (right) passengers aboard

2.2 Computational grid

Due to very complex geometry of the computational domain, an unstructured tetrahedral computational grid with more than 3 million cells was used. Not to have to solve the problem with and without the passengers aboard as two different problems with different meshes, the passenger body volumes were designed and meshed as separate cell zones. Activating and deactivating the passengers' cell zones enabled us to compute these two options.

3 MATHEMATICAL MODEL OF A COOL AIR FLOW

A cool air flow inside a closed computational domain $\Omega \subset R^3$ with a boundary $\partial\Omega$ is solved as an unsteady natural convection problem. Such problem involves a coupling between the Navier-Stokes equations describing the fluid motion and the thermal energy equation governing the space-time evolution of the temperature, which is made through the Boussinesq approximation[2,3]. The forces which induce natural convection are in fact spatially variable gravity forces generated by density variations in the fluid due to the non-uniformity of the temperature. The cool air is assumed incompressible according to Boussinesq approximation. In this approximation, the density of the fluid is taken as a constant everywhere in the momentum and energy equations except in the gravity force term. There the density depends on temperature according to the following equation:

$$\rho = \rho_0 [1 - \beta (T - T_0)] \tag{1}$$

where β is the volume thermal expansion coefficient of the fluid, $T(\boldsymbol{y},t)$ is the temperature field, T_0 is the reference temperature and $\rho_0 = \rho(T_0)$ is the reference density of the fluid. For natural convection, the body force term $\boldsymbol{f}$ is equal to the gravity acceleration $\boldsymbol{g}$.

In natural convection problems the mathematical description of the unsteady incompressible viscous Newtonian fluid flow is given by the following generalized system of the incompressible Navier-Stokes equations, the so-called Boussinesq equations[2]:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{2}$$

$$\rho_0 \left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla) \boldsymbol{v} \right) = -\nabla p + \eta \, \Delta \boldsymbol{v} + \rho_0 [1 - \beta (T - T_0)] \, \boldsymbol{g} \tag{3}$$

$$\rho_0 \, c_p \left(\frac{\partial T}{\partial t} + \boldsymbol{v} \cdot \nabla T \right) = \nabla \cdot (k \, \nabla T) + \rho_0 \, r + \eta \Phi \tag{4}$$

in the space-time cylinder $\Omega_T = \Omega \times \left]0,\tau\right[$, where t is time, $\boldsymbol{v} = [v_1, v_2, v_3]^T$ is the velocity vector, p is the static pressure c_p denotes the specific heat of the fluid at constant pressure, k is the thermal conductivity and the molecular viscosity η is constant. The symbol $\Delta = \partial^2 / \partial y_j \partial y_j$ represents the Laplacian operator. The last term in the right hand side of (3) is the buoyancy force that drives the motion by the temperature differences in the physical domain of the flow. In our application, the volumetric heat generation $\rho_0 \, r$ and the viscous dissipation term Φ in (4), defined in literature[4], do not appear.

This set of non-linear equations (2) – (4) is to be solved subject to boundary and initial conditions. For the temperature equation (4) typically two types of boundary conditions are frequently specified. In the first category, the wall temperature (or its distribution along the wall) is provided:

$$T(\boldsymbol{y},t) = T_w(\boldsymbol{y},t) \quad \text{on} \quad \Gamma^T_{wD} \times \left]0,\tau\right[\tag{5}$$

In the second category, an adiabatic wall is specified requiring zero heat transfer at the surface. Recall that the heat transfer rate is frequently expressed in terms of the heat transfer coefficient h given by:

$$h = \frac{-k \left(\dfrac{\partial T(\boldsymbol{y},t)}{\partial n} \right)}{T - T_\infty} \quad \text{on} \quad \Gamma^T_{wN} \times \left]0,\tau\right[\tag{6}$$

where n designates the direction normal to the surface and T_∞ is the exterior (free stream) temperature.

4 NUMERICAL SOLUTION AND SETTINGS

All numerical simulations have been performed using the professional software package Fluent, version 6.2. In our computational models is supposed that the 06T-Cagliari tram is operated in conditions, where the external environment temperature is $42°C \approx 315\ K$. It follows, according to the company documentation[8], that the air-conditioner is able to cool down the air temperature on the value of $37°C \approx 310\ K$. So, the air temperature inside the passenger space should be about $310\ K$. It is related to 4 standing persons per square meter.

A cool air is assumed incompressible according to Boussinesq approximation mentioned above. The Boussinesq parameters (thermal expansion coefficient β of the air, the reference/operating temperature T_0 and the reference/operating density ρ_0 of the air) in (1) have been set in the following way: $\beta = 0.0032\ K^{-1}$, $T_0 = 315\ K$ and $\rho_0 = 1.127\ kg\,m^{-3}$.

The cool air flow inside the closed tram passenger space has been solved as an unsteady turbulent flow of incompressible viscous Newtonian fluid with the constant molecular viscosity $\eta = 1.7894 \cdot 10^{-5}\,kg\,m^{-1}s^{-1}$ and constant thermal conductivity $k = 0.0242\,W\,m^{-1}K^{-1}$. For the computation of turbulent viscosity, the one-equation Spalart-Allmaras turbulence model with default model constants[1,4] has been used.

On the boundary $\partial\Omega$ of the computational domain $\Omega \subset R^3$, see Figure 2, following boundary conditions have been considered. At the inlet $\partial\Omega_I$, the constant mass flow rate $\dot{m} = 0.2892\ kg\,s^{-1}$ of the cool air has been defined according to the distribution computed in our paper[5] and the total temperature of $310\ K$ has been also prescribed. At the outlet $\partial\Omega_O$, the static pressure $p = 0\ Pa$ has been kept because the operating pressure p_{op} has the value of atmospheric pressure $101325\,Pa$. On the boundary $\partial\Omega_S$, the boundary condition of symmetry has been applied. On the solid walls $\partial\Omega_W$ of the computational domain the no slip boundary conditions have been realized. The thermal boundary condition (6), with nonzero heat transfer coefficient h and free stream temperature $T_\infty = 315\ K$, has been satisfied on the following solid walls of the considered internal passenger space: left and right sidewalls, floor, top, door and windows. The values of the heat transfer coefficient h are listed in Table 1. On the rest of solid walls of the computational domain Ω, zero heat transfer (adiabatic walls) has been assumed.

Type of the solid wall	**Heat transfer coefficient** $h\ [W\,m^{-2}K^{-1}]$
left and right sidewalls, top	0.93
floor	1.05
door	8.0
windows	10.0

Table 1 : Heat transfer coefficients

For numerical computations, the segregated solver in 3D based on the unsteady implicit formulation of the second order upwind scheme has been used.

5 NUMERICAL RESULTS AND DISCUSSION

In this paragraph, the results of the numerical simulations of a cool air flow inside the passenger space of the first part of 06T-Cagliari tram are presented for two computational models – without and with passengers aboard.

In Figure 3 and Figure 4, the contours of velocity magnitude distribution in the selected vertical planes throughout the passenger space are visualized.

In Figure 5 and Figure 6, the contours of velocity magnitude distribution at time $t = 300\ s$ are shown in two horizontal cross-sections – in the sitting passengers' heads high and in the standing passengers' heads high. It is observed, that the maximum value of the velocity in the sitting passengers' heads high is $v_{max} = 0.751\ m\,s^{-1}$ and in the standing passengers' heads high is $v_{max} = 0.996\ m\,s^{-1}$. These computed values of the velocity satisfy the required limiting value published in the standard[6], which says that the air flow velocity up to $2\ m\,s^{-1}$ is accepted inside the passenger space for the exterior air temperature greater than $26\,°C$ (this is our case).

In Figure 7 and Figure 8, the contours of static temperature distribution in the selected vertical planes throughout the computational domain are presented.

In Figure 9 and Figure 10, the contours of static pressure distribution in the same vertical planes throughout the computational domain are shown.

To visualize the cool air flow in the internal passenger space, the path lines colored by static temperature lead from the inlet gaps of the longitudinal air channels are presented in Figure 11.

It is observed from all performed numerical computations that the convergence is worse for the continuity equation, for which the residuals did not drop bellow the value 10^{-3}. The obtained results are satisfying because the difference between the mass flow rate at the inlet $\partial\Omega_I$ and at the outlet $\partial\Omega_O$ is smaller than the value $10^{-8}\ kg\,s^{-1}$.

As mentioned in the company documentation[8], one of the important air-conditioning specifications is the number N, which express how many times per hour an air change occurs inside the passenger space. According to the relation:

$$N = \frac{\dot{m}}{\rho \cdot V_{int}} \tag{7}$$

where $\dot{m}$ is the mass flow rate of the cool air entering (and exiting) the computational domain and $V_{int} = 20.416\ m^3$ is the volume of the computational domain (the interior of the considered tram passenger space), it can be computed that $N \approx 42$ for the internal passenger space of the first part of 06T-Cagliari tram.

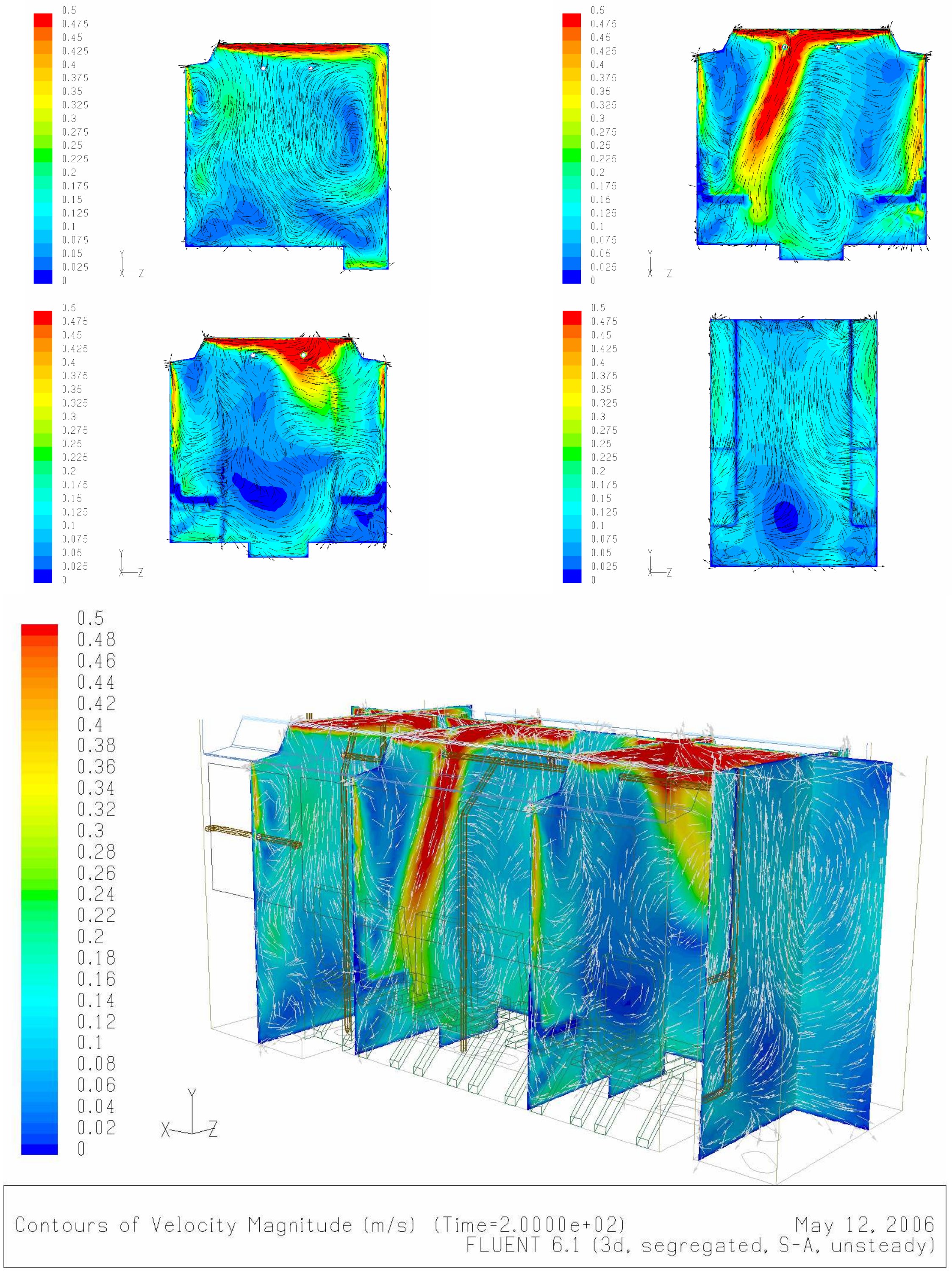


Figure 3: Contours of velocity magnitude [*m/s*] inside the passenger space without passengers aboard in selected cross-sections at time t = *200 s* (at the top) and general view (at the bottom)

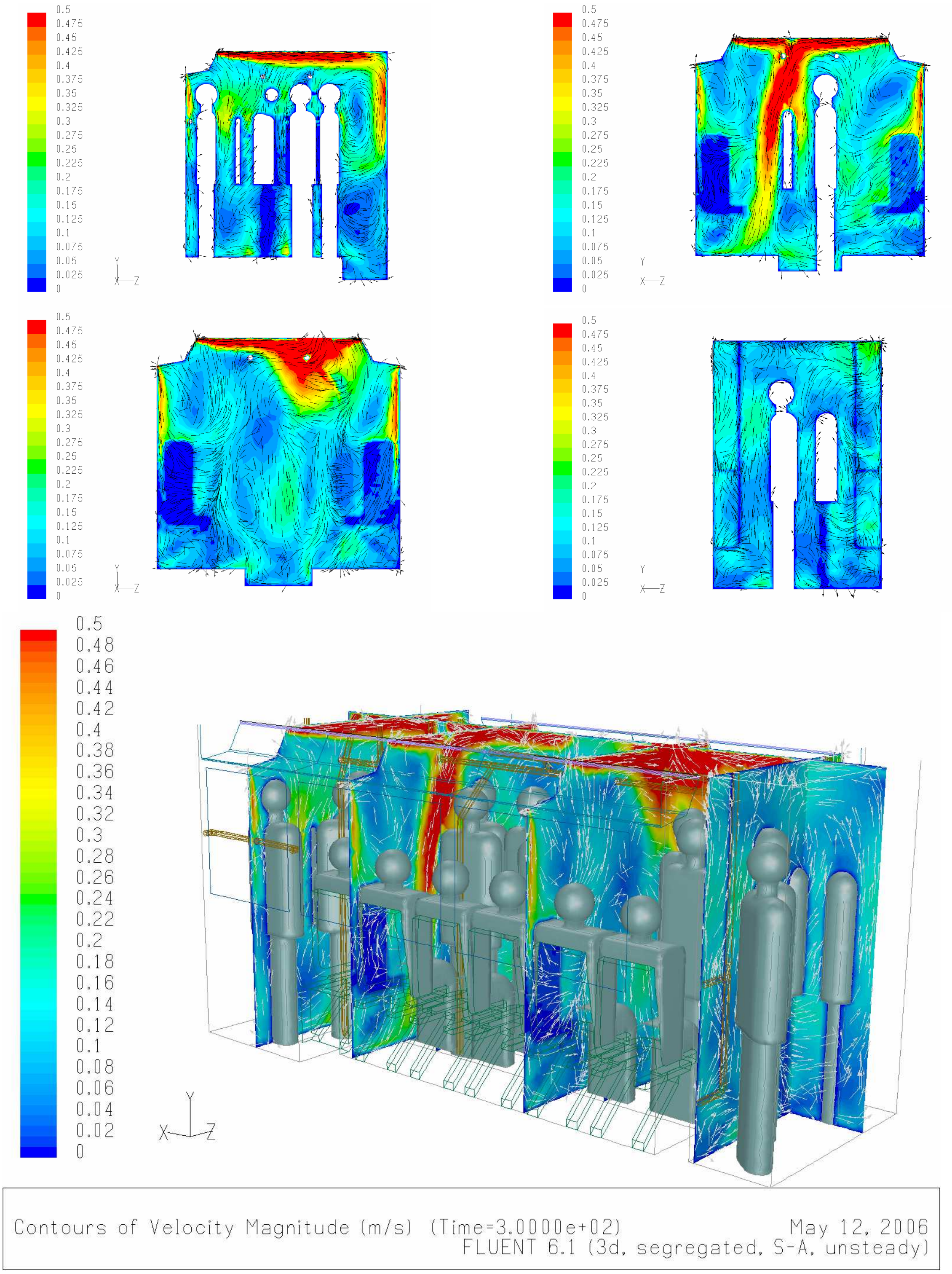


Figure 4: Contours of velocity magnitude [*m/s*] inside the passenger space with passengers aboard in selected cross-sections at time $t = 300\ s$ (at the top) and general view (at the bottom)

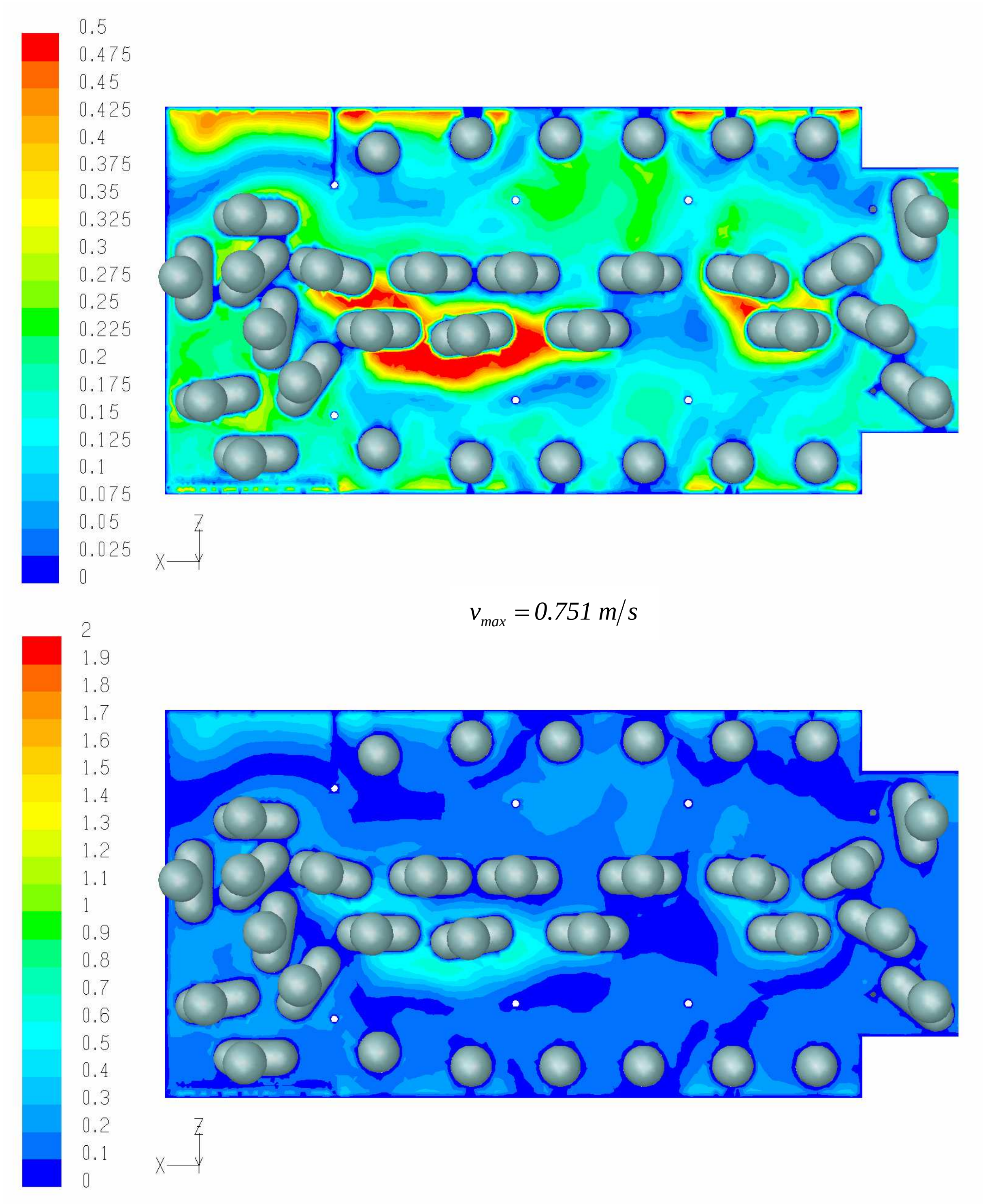


Figure 5: Contours of velocity magnitude [*m/s*] at time $t = 300\ s$ in the horizontal cross-section in the sitting passengers' heads high for two different velocity ranges – up to *0.5 m/s* (at the top) and up to *2.0 m/s* (at the bottom)

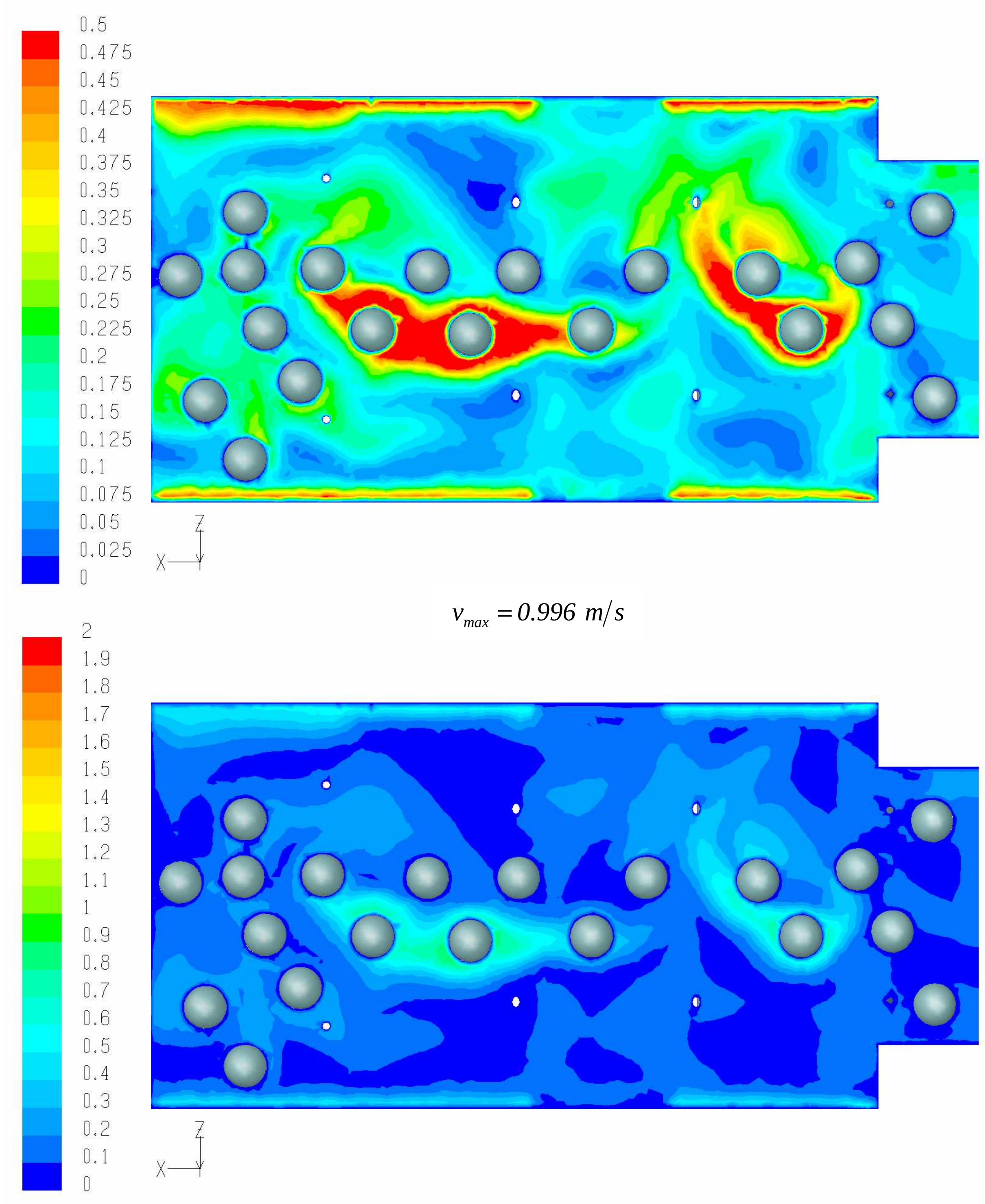


Figure 6: Contours of velocity magnitude [*m/s*] at time $t = 300\ s$ in the horizontal cross-section in the standing passengers' heads high for two different velocity ranges – up to *0.5 m/s* (at the top) and up to *2.0 m/s* (at the bottom)

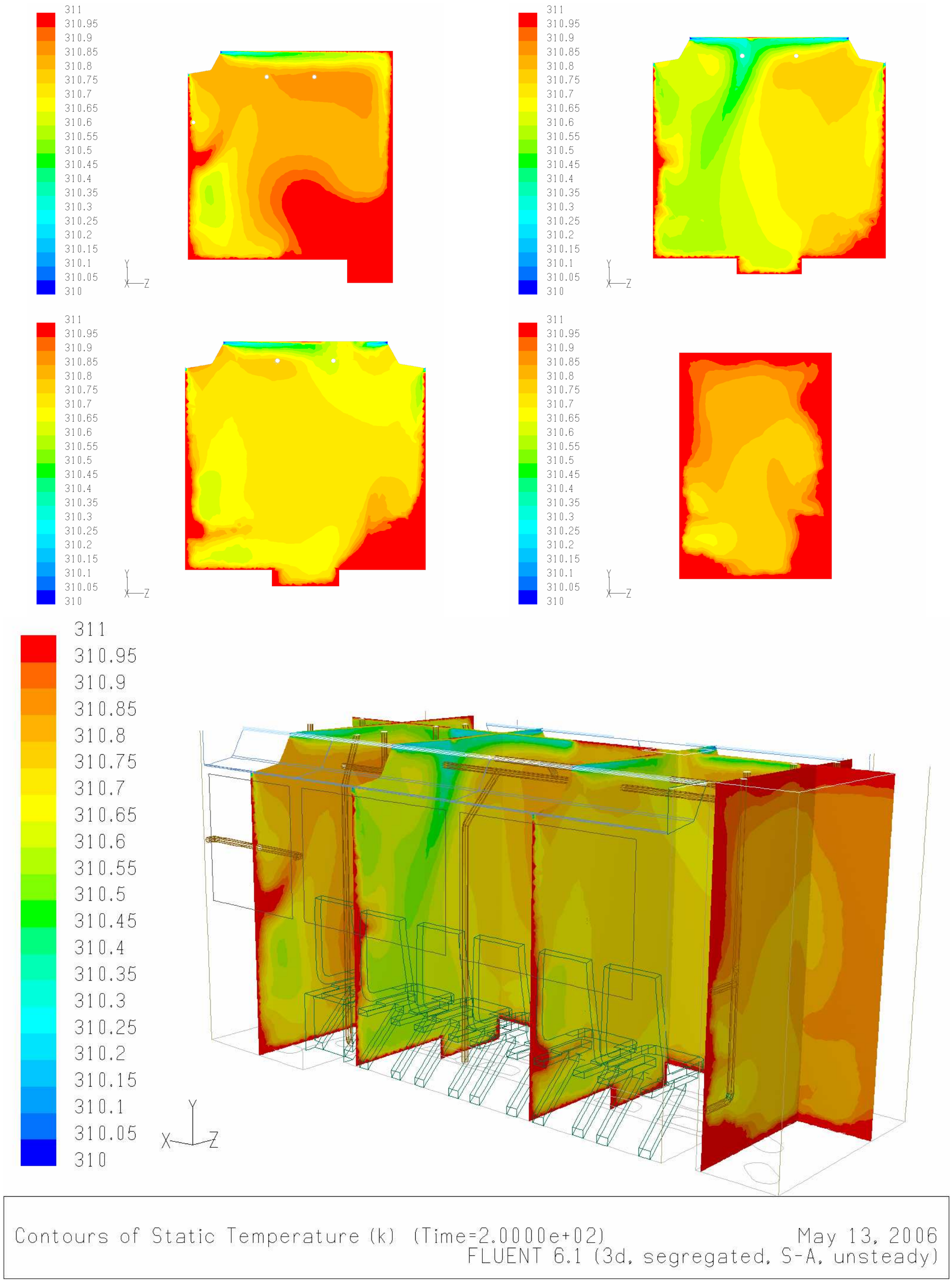


Figure 7: Contours of static temperature [K] inside the passenger space without passengers aboard in selected cross-sections at time t = *200 s* (at the top) and general view (at the bottom)

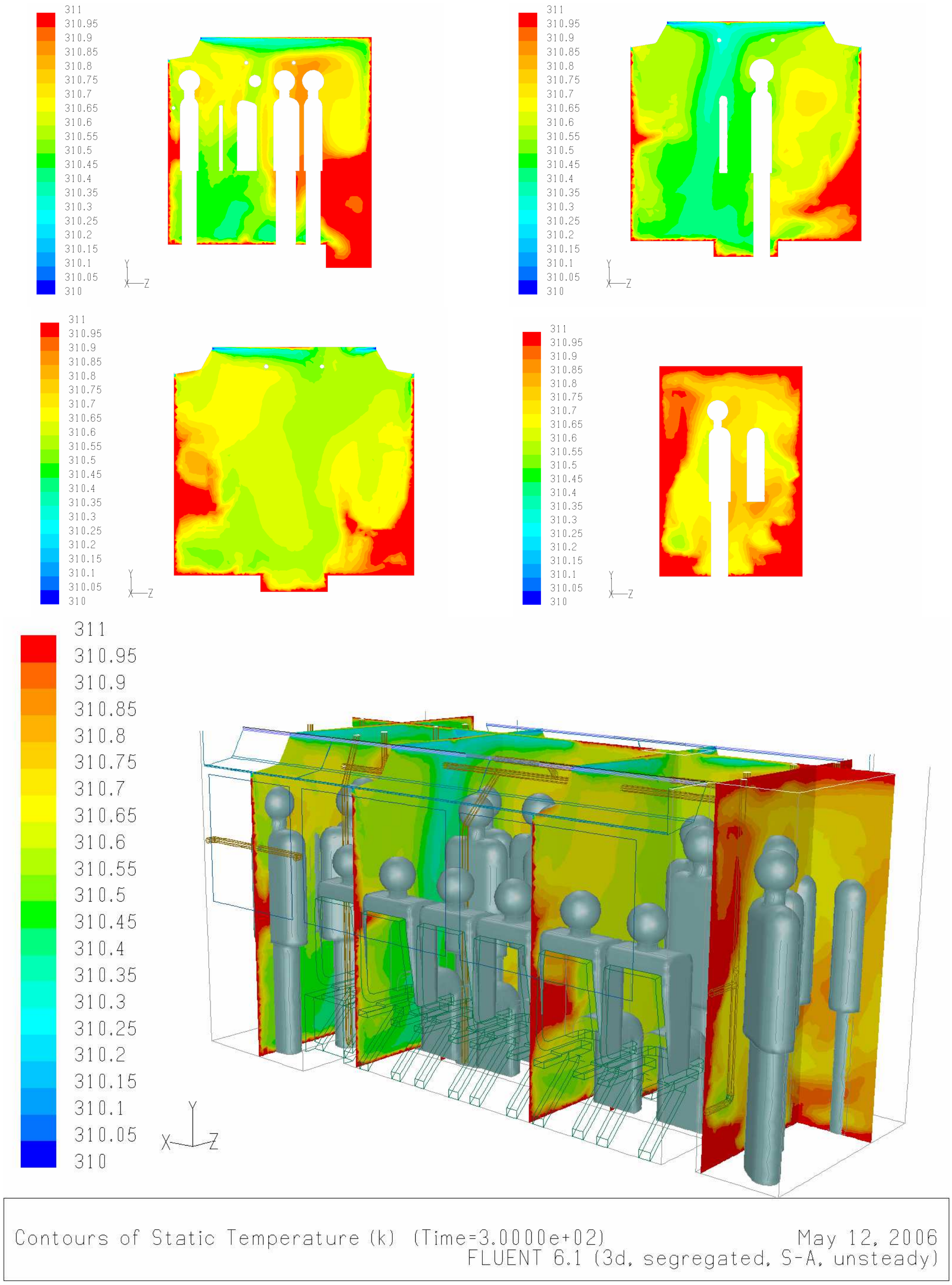


Figure 8: Contours of static temperature [K] inside the passenger space with passengers aboard in selected cross-sections at time t = 300 s (at the top) and general view (at the bottom)

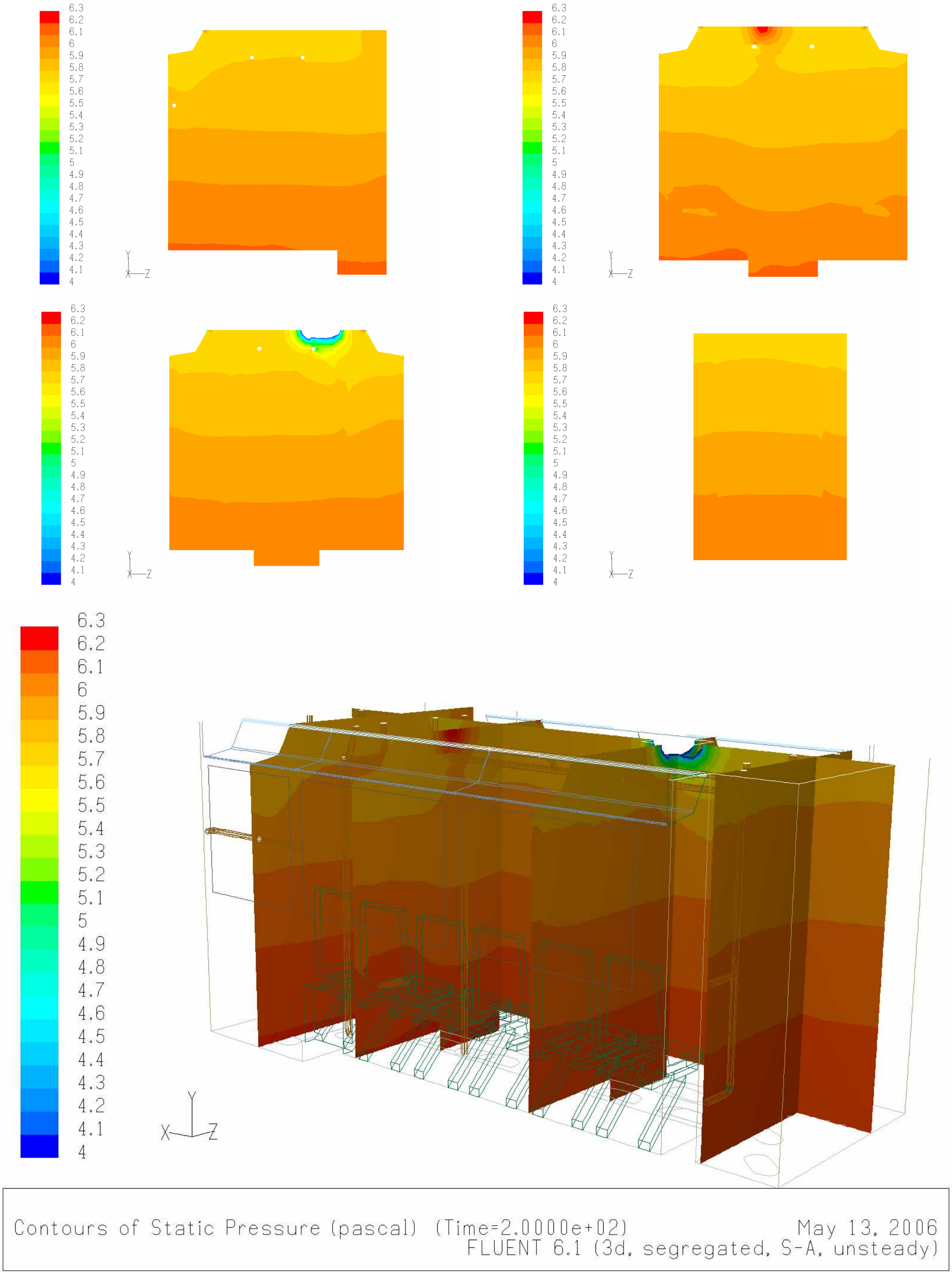


Figure 9: Contours of static pressure [*Pa*] inside the passenger space without passengers aboard in selected cross-sections at time t = *200 s* (at the top) and general view (at the bottom)

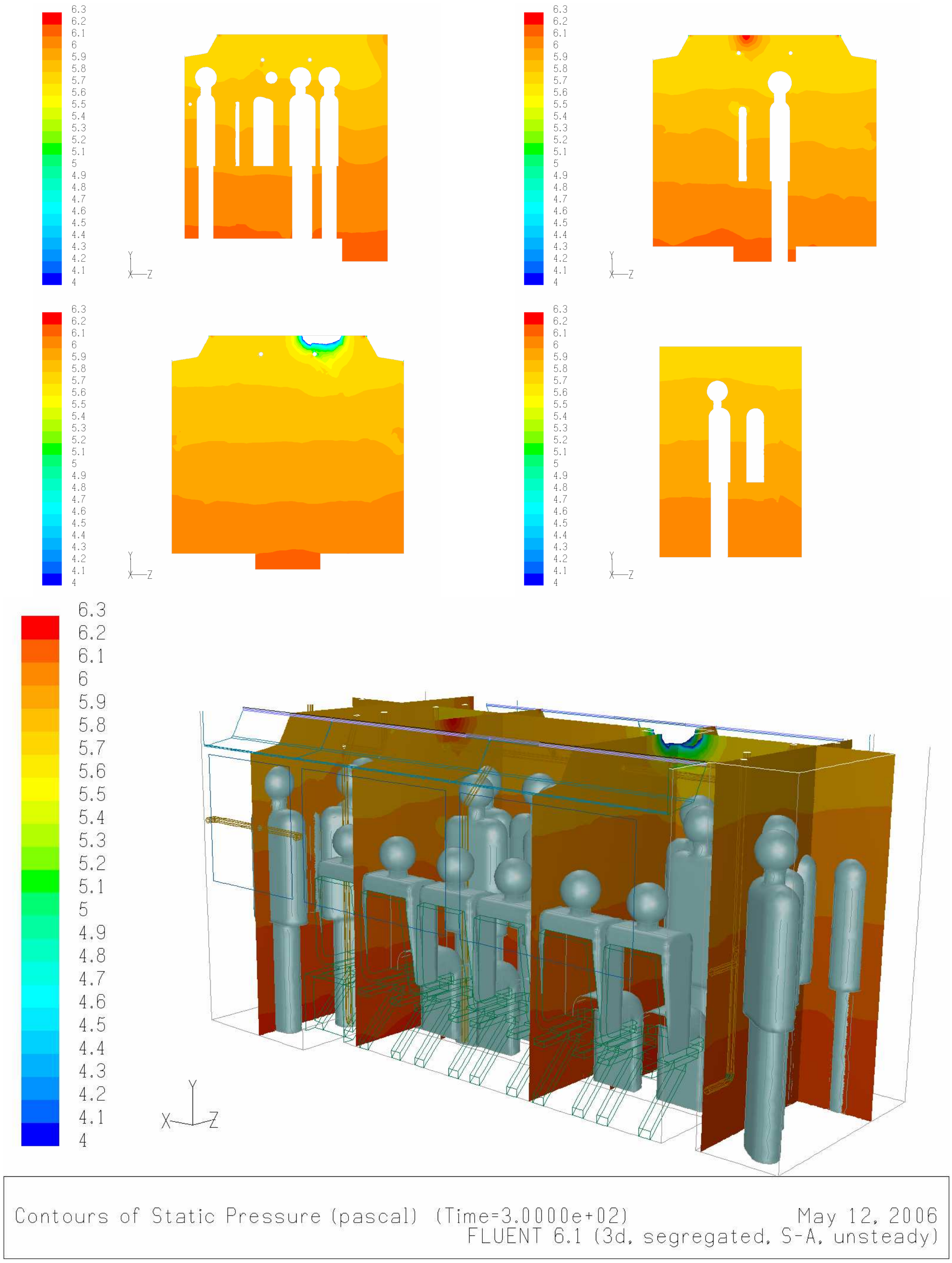
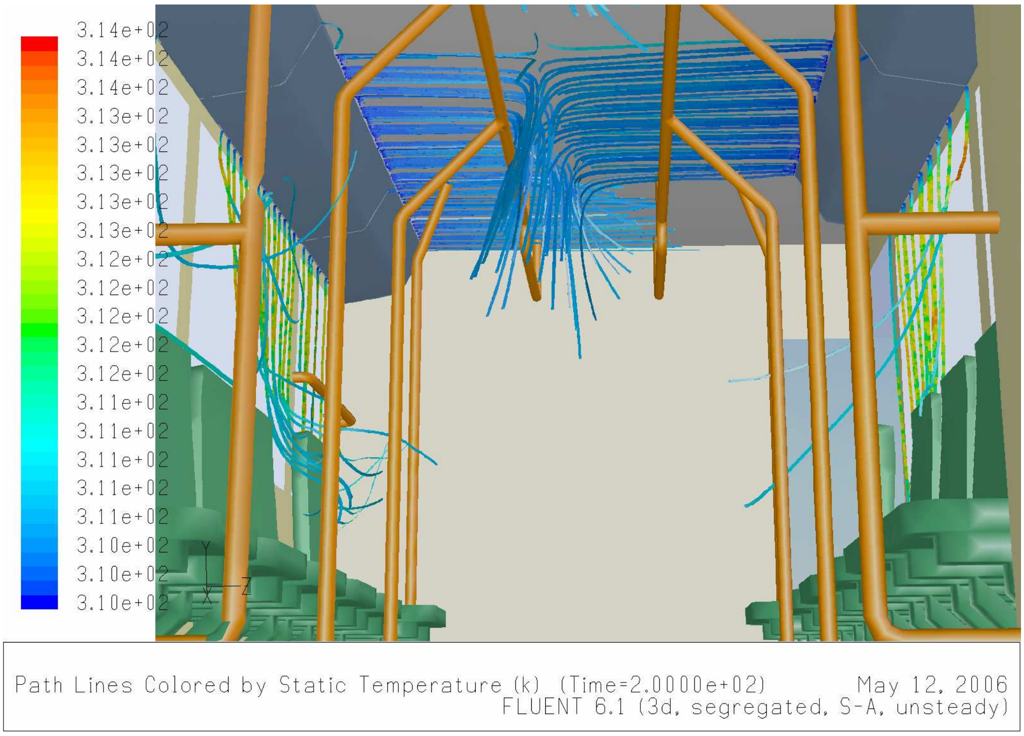


Figure 10: Contours of static pressure [*Pa*] inside the passenger space with passengers aboard in selected cross-sections at time t = *300 s* (at the top) and general view (at the bottom)



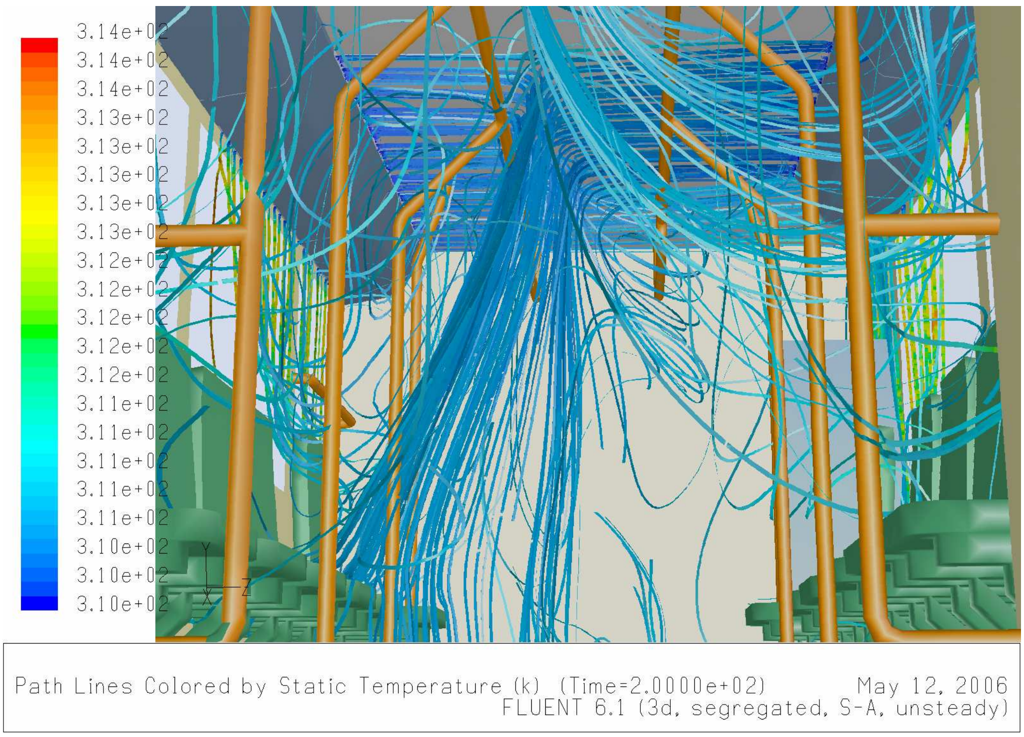


Figure 11: Spread out of path lines lead from the inlet longitudinal gaps colored and twisted by static temperature [K] inside the passenger space without passengers aboard

6 CONCLUSIONS

As a conclusion of this numerical testing it can be deduced that the computed results (velocity magnitude and static temperature) of the cool air flow inside the first part of 06T-Cagliari tram passenger space correspond to the available relevant standard.

It is observed, that the maximum computed values of the velocity in the sitting passengers' heads high and in the standing passengers' heads high satisfy the required limiting value published in the standard[6] for our case. It has been computed that an air change occurs 42 times per hour inside the passenger space of the first part of 06T-Cagliari tram.

The convergence of the continuity equation is worse, but we suppose that the accuracy of the obtained numerical results is satisfactory.

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