



Thermal and Fluid-dynamical Optimisation of Passengers Comfort in a Touring Bus Cabin

Petrone G., Fichera G., Scionti M.



Presented by G. Petrone



Outlines of presentation

- ✓ Bus-Engineering Company presentation
- ✓ Introduction to “Thermal and Fluid-dynamical comfort”
- ✓ Modeling of a touring bus cabin by COMSOL Multiphysics
- ✓ Analysis of results
- ✓ Conclusion & Perspectives



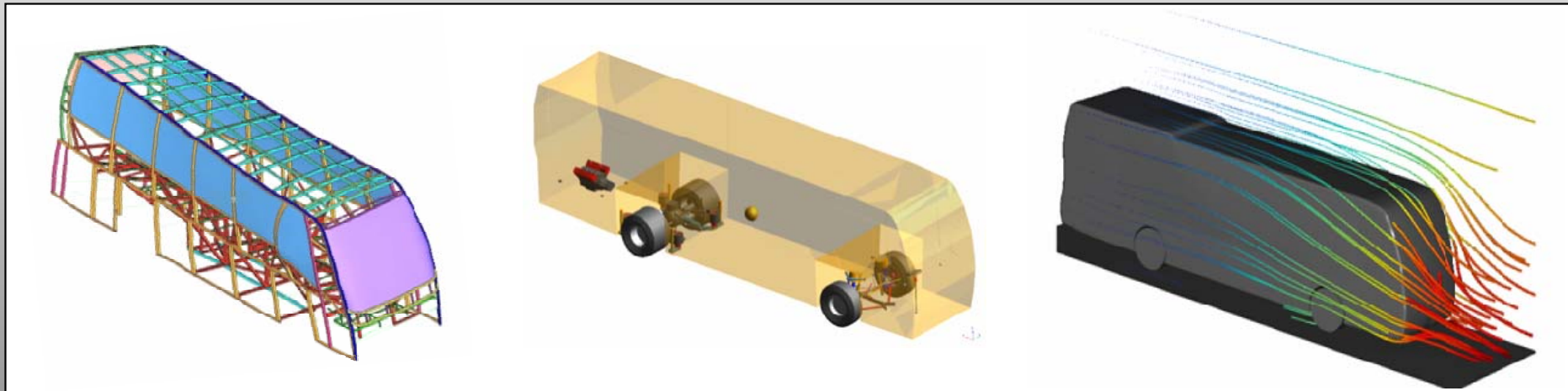
Outlines of presentation

- ✓ **Bus-Engineering Company presentation**
- ✓ Introduction to “Thermal and Fluid-dynamical comfort”
- ✓ Modeling of a touring bus cabin by COMSOL Multiphysics
- ✓ Analysis of results
- ✓ Conclusion & Perspectives



Who is Bus-Engineering?

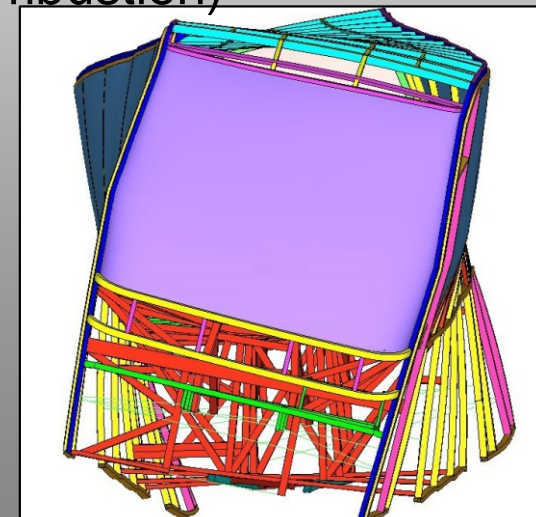
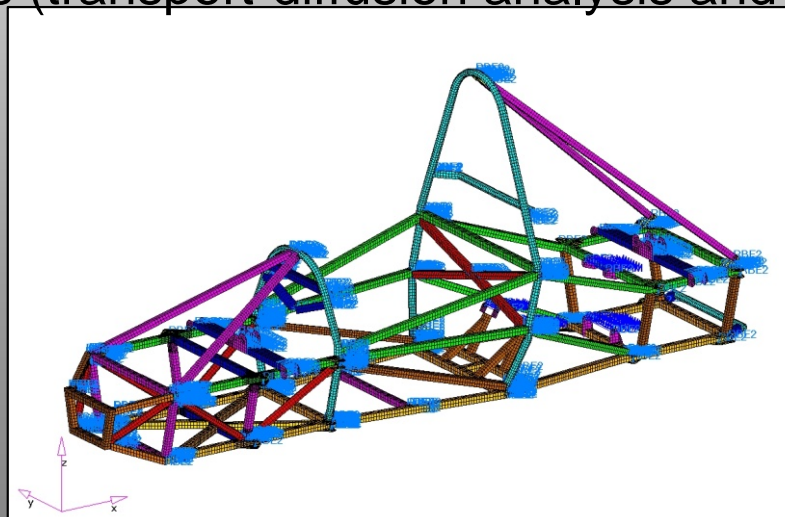
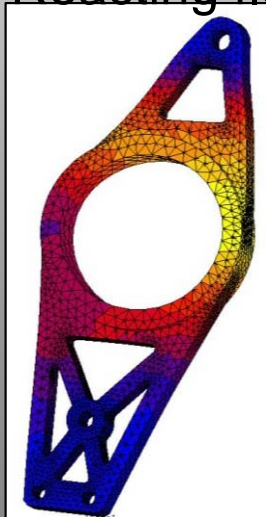
Bus-Engineering provides consultancy services for applications based on numerical simulations offering support and assistance to those professionals and enterprises aimed at analyzing complex problems related to their technical activities





Bus-Engineering's main areas of expertise include:

- ✓ **Structural mechanics (static linear and non-linear analysis, modal analysis)**
- ✓ Multibody system dynamics (kinematics and dynamics of mechanical systems)
- ✓ Fluid-dynamics (laminar, turbulent and two-phase flow)
- ✓ Heat transfer (conduction, convection and radiation analysis)
- ✓ Reacting flows (transport-diffusion analysis and combustion)

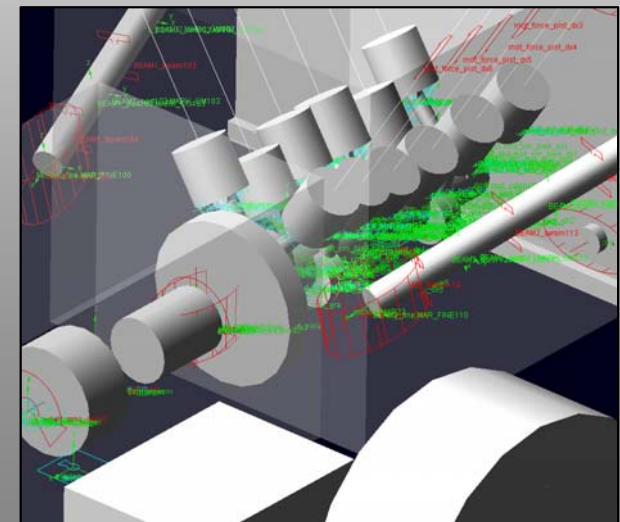
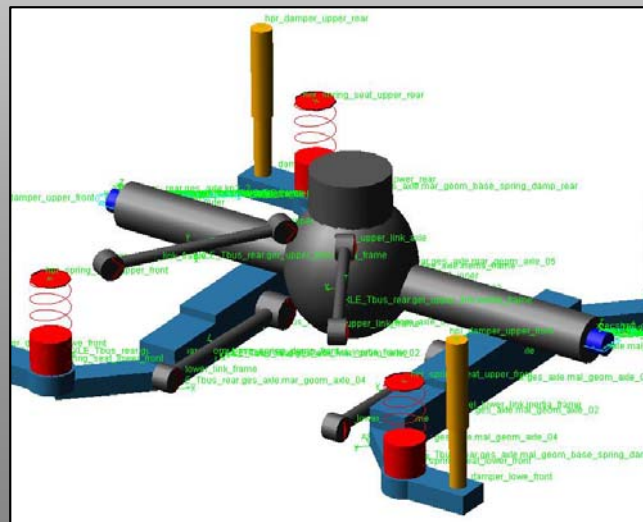
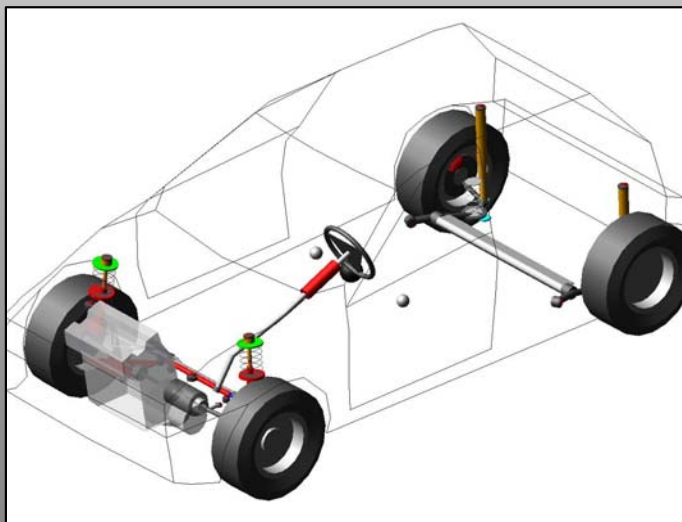




Fields of Activities

Bus-Engineering's main areas of expertise include:

- ✓ Structural mechanics (static linear and non-linear analysis, modal analysis)
- ✓ **Multibody system dynamics (kinematics and dynamics of mechanical systems)**
- ✓ Fluid-dynamics (laminar, turbulent and two-phase flow)
- ✓ Heat transfer (conduction, convection and radiation analysis)
- ✓ Reacting flows (transport-diffusion analysis and combustion)

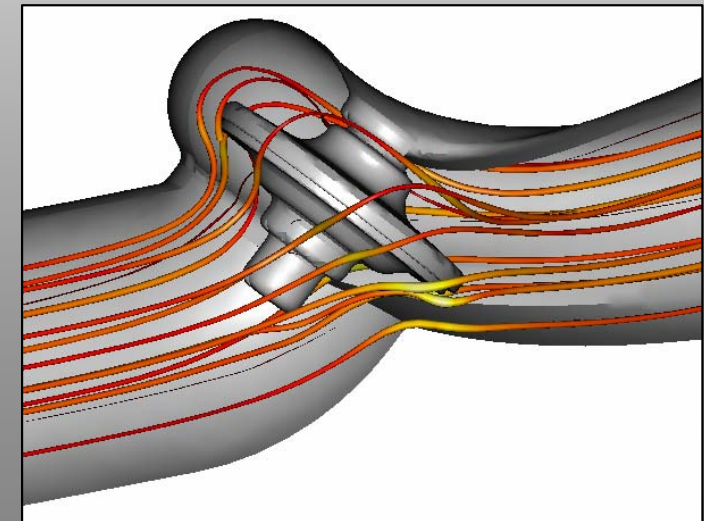
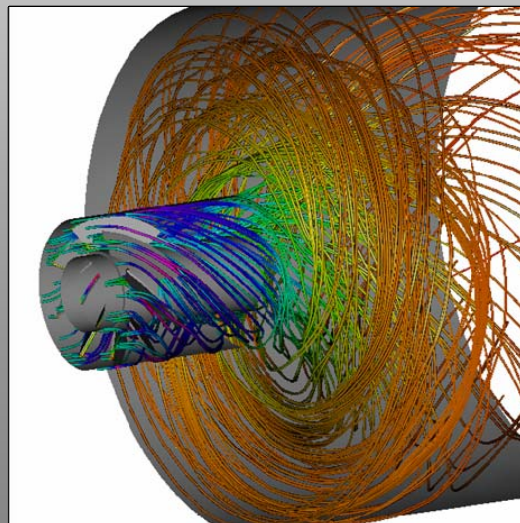
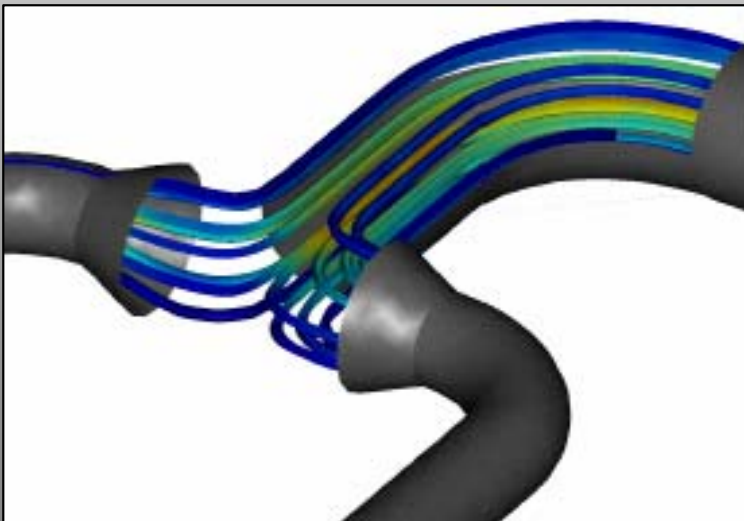




Fields of Activities

Bus-Engineering's main areas of expertise include:

- ✓ Structural mechanics (static linear and non-linear analysis, modal analysis)
- ✓ Multibody system dynamics (kinematics and dynamics of mechanical systems)
- ✓ **Fluid-dynamics (laminar, turbulent and two-phase flow)**
- ✓ Heat transfer (conduction, convection and radiation analysis)
- ✓ Reacting flows (transport-diffusion analysis and combustion)

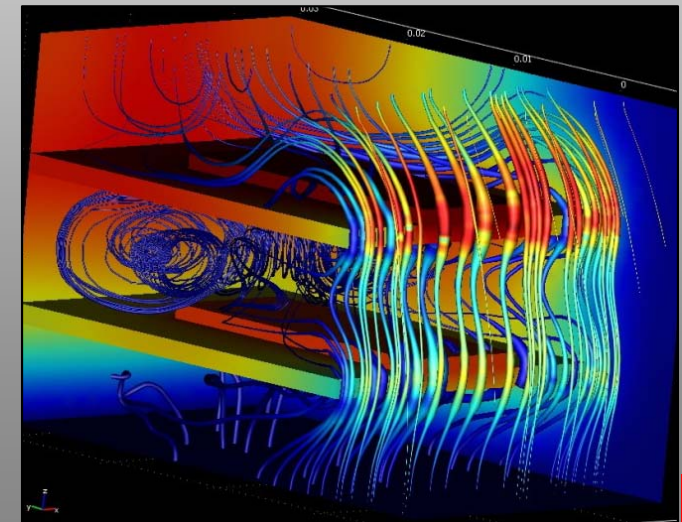
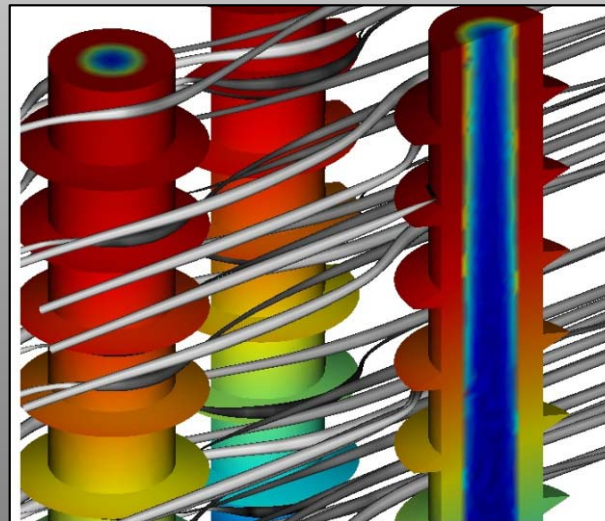
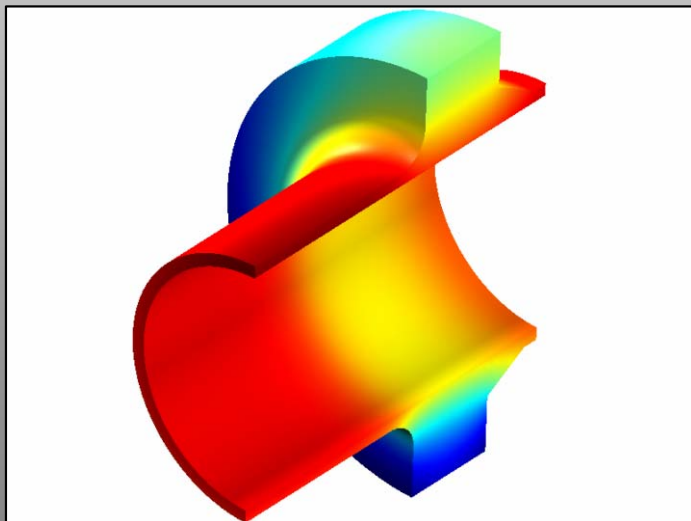




Fields of Activities

Bus-Engineering's main areas of expertise include:

- ✓ Structural mechanics (static linear and non-linear analysis, modal analysis)
- ✓ Multibody system dynamics (kinematics and dynamics of mechanical systems)
- ✓ Fluid-dynamics (laminar, turbulent and two-phase flow)
- ✓ **Heat transfer (conduction, convection and radiation analysis)**
- ✓ Reacting flows (transport-diffusion analysis and combustion)

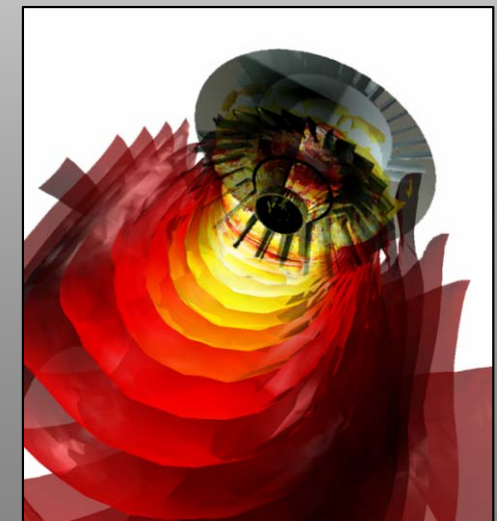
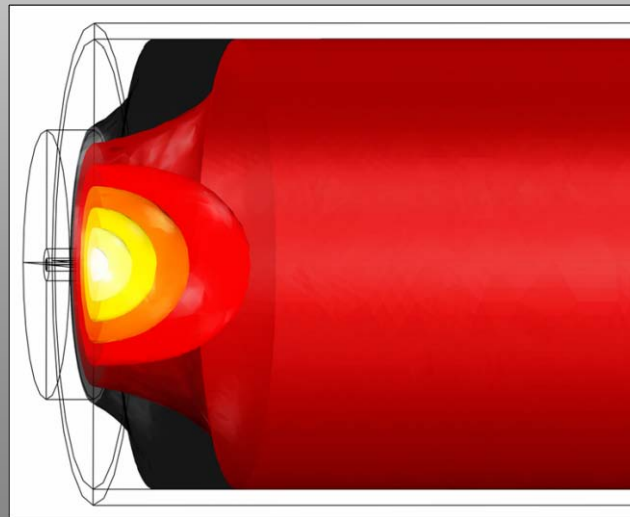
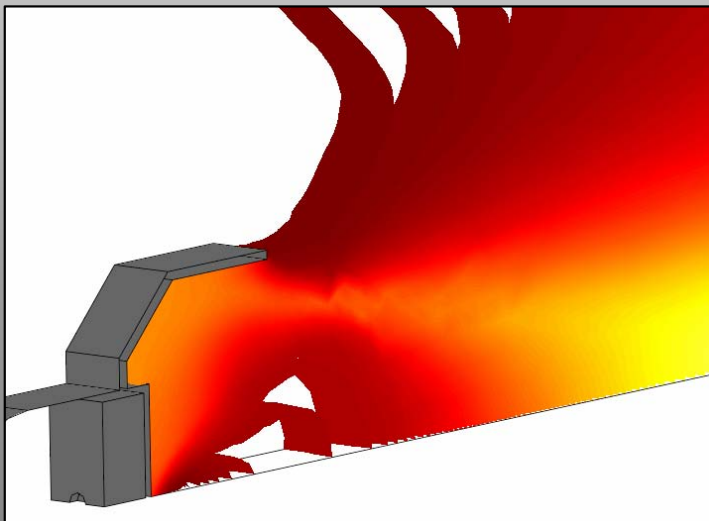




Fields of Activities

Bus-Engineering's main areas of expertise include:

- ✓ Structural mechanics (static linear and non-linear analysis, modal analysis)
- ✓ Multibody system dynamics (kinematics and dynamics of mechanical systems)
- ✓ Fluid-dynamics (laminar, turbulent and two-phase flow)
- ✓ Heat transfer (conduction, convection and radiation analysis)
- ✓ **Reacting flows (transport-diffusion analysis and combustion)**





Partnership

Thanks to experience gained in the numerical simulation field, Bus-Engineering is today a COMSOL Certified Consultant



“... The COMSOL Group provides software solutions for multiphysics modeling...”



Outlines of presentation

- ✓ Bus-Engineering Company presentation
- ✓ Introduction to “Thermal and Fluid-dynamical comfort”
- ✓ Modeling of a touring bus cabin by COMSOL Multiphysics
- ✓ Analysis of results
- ✓ Conclusion & Perspectives



Thermal and Fluid-dynamical comfort

Human thermal comfort is defined by ASHRAE as the state of mind that expresses satisfaction with the surrounding environment (ASHRAE Standard 55). Maintaining thermal comfort for occupants of buildings or other enclosures is one of the important goals of HVAC design engineers.

Thermal comfort is affected by heat conduction, convection, radiation, and evaporative heat loss.

Thermal comfort is maintained when the heat generated by human metabolism is allowed to dissipate, thus maintaining thermal equilibrium with the surroundings. Any heat gain or loss beyond this generates a sensation of discomfort.

It has been long recognized that the **sensation of feeling hot or cold is not just dependent on air temperature alone.**



Thermal and Fluid-dynamical comfort

Factors determining comfort include:

- ✓ Air temperature
- ✓ Mean radiant temperature
- ✓ Air velocity
- ✓ Relative humidity
- ✓ Insulating clothing
- ✓ Activity levels



Thermal and Fluid-dynamical comfort

Many of the studies on this topic led to the development and refinement of ASHRAE Standard 55 and were performed at Kansas State University by **Ole Fanger** and others.

Perceived comfort was found to be a complex interaction of these variables. It was found that the majority of individuals would be satisfied by an ideal set of values.

As the range of values continued to deviate from ideal, increasingly fewer people were satisfied. This observation could be expressed statistically as the % of individual who expressed satisfaction by comfort conditions and the predicted mean vote (PMV).



Thermal and Fluid-dynamical comfort

From an operative point of view in designing heating and ventilating systems it should be assured:

- ✓ **low air velocities and no 'drafts' effects**
- ✓ **slight variation in temperature from different directions of the environment**



Thermal and Fluid-dynamical comfort

Thermal comfort plays a crucial role in public transports, much more than in building applications.

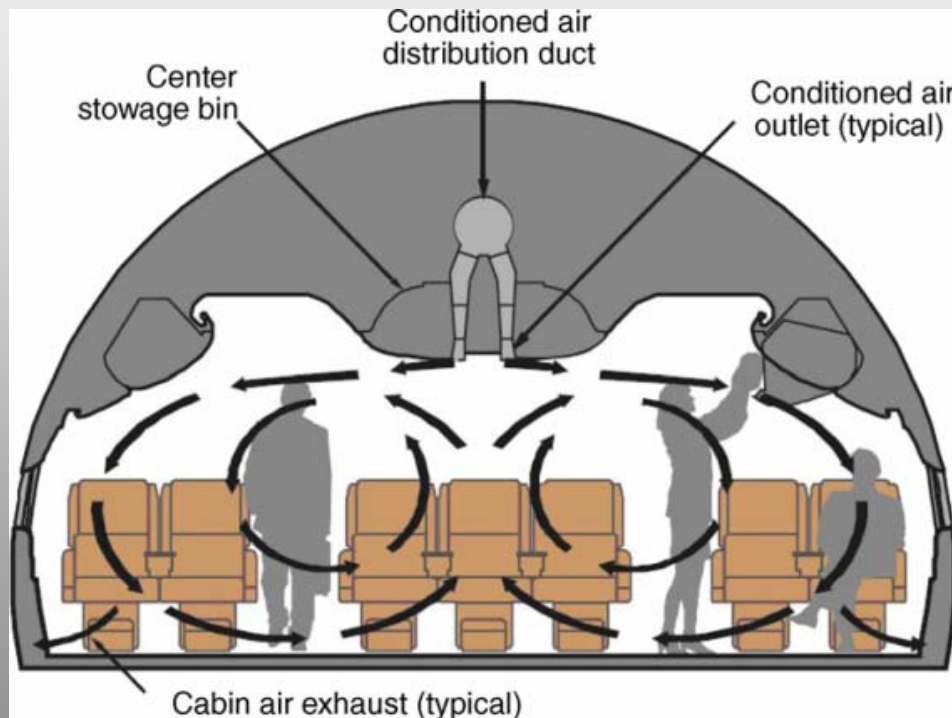
In fact **passengers, standing inside a cabin for several hours, do not have large opportunities of moving.**

This is the reason why since several years many studies have been devoted to the air distribution system for passengers cabin.



Thermal and Fluid-dynamical comfort

Several bibliographic studies concern ventilation and thermal comfort conditions in aircraft cabin ...



- Zhang T., Chen Q., Novel air distribution systems for commercial aircraft cabins, *Building and Environment*, Vol. 42 (2007), pp. 1675-1684.
- Aijun W., Yuanhui Z., Yigang S., Xinlei W., Experimental study of ventilation effectiveness and air velocity distribution in an aircraft cabin mockup, *Building and Environment*, Vol. 43 (2008), pp. 337-343.



Thermal and Fluid-dynamical comfort

... however **no many studies have focused on air distribution system in touring bus cabin**, in spite of comparable traveling time for aircraft and touring-bus passengers.



Thermal and Fluid-dynamical comfort

... however **no many studies have focused on air distribution system in touring bus cabin**, in spite of comparable traveling time for aircraft and touring-bus passengers.

- The present communication deals with an **investigation on the most appropriate layout for the ventilation air inlets in a touring bus cabin** in order to optimize thermal and fluid-dynamical conditions for passengers.
- In particular, **two inlet sections for fresh air are considered**: the **first one**, located at the roof and representative of a ceiling **mixing air distribution**, is made of rectangular slots positioned in the horizontal channel developing along the cabin aisle; **the second one**, representative of a **displacement ventilation system**, is located in correspondence of the lateral side of each seat.

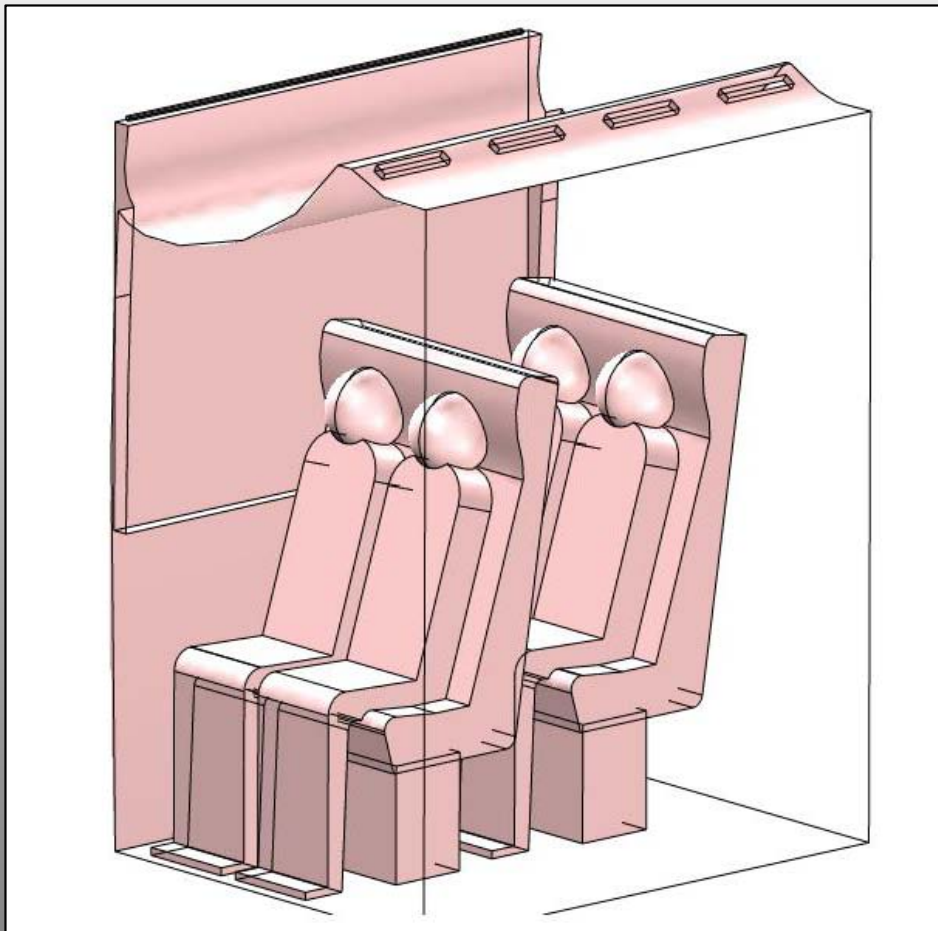


Outlines of presentation

- ✓ Bus-Engineering Company presentation
- ✓ Introduction to “Thermal and Fluid-dynamical comfort”
- ✓ Modeling of a touring bus cabin by COMSOL Multiphysics
- ✓ Analysis of results
- ✓ Conclusion & Perspectives

Numerical modeling

The geometry of the system consists in a portion of the bus cabin, containing two rows of seats:



Contrary to **building applications**, where furnishing and **people position is difficult to predict**, so that simulations are very often carried-out for empty rooms, in **transport applications** the **passengers' position is well-known**, so that some geometrical elements have been used in this model in order to simulate the human presence.



Numerical modeling

Momentum and energy equations have been solved adopting a k-ε scheme for turbulence modeling:

$$\rho u \cdot \nabla u = \nabla \cdot \left[-pI + (\eta + \eta_T)(\nabla u + (\nabla u))^T \right] + F$$

$$\nabla \cdot (\rho u) = 0$$

$$\rho u \cdot \nabla k = \nabla \cdot \left[\left(\eta + \frac{\eta_T}{\sigma_k} \right) \nabla k \right] + \eta_T P(u) - \rho \varepsilon$$

$$\rho u \cdot \nabla \varepsilon = \nabla \cdot \left[\left(\eta + \frac{\eta_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \frac{C_{\varepsilon 1} \varepsilon \eta_T P(u)}{k} - \frac{C_{\varepsilon 2} \rho \varepsilon^2}{k}$$

Temperature field has been computed by solving energy conservation equation:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q - \rho C_p u \cdot \nabla T$$



Numerical modeling

Boundary conditions for fluid-dynamical analysis:

- ✓ No-slip condition at solid walls;
- ✓ Chosen velocity for incoming air through the inlet slots of the air distribution system;
- ✓ Chosen pressure correspondence of the recovery grid for air;
- ✓ Symmetry conditions for the longitudinal and transversal confinement of the air volume;

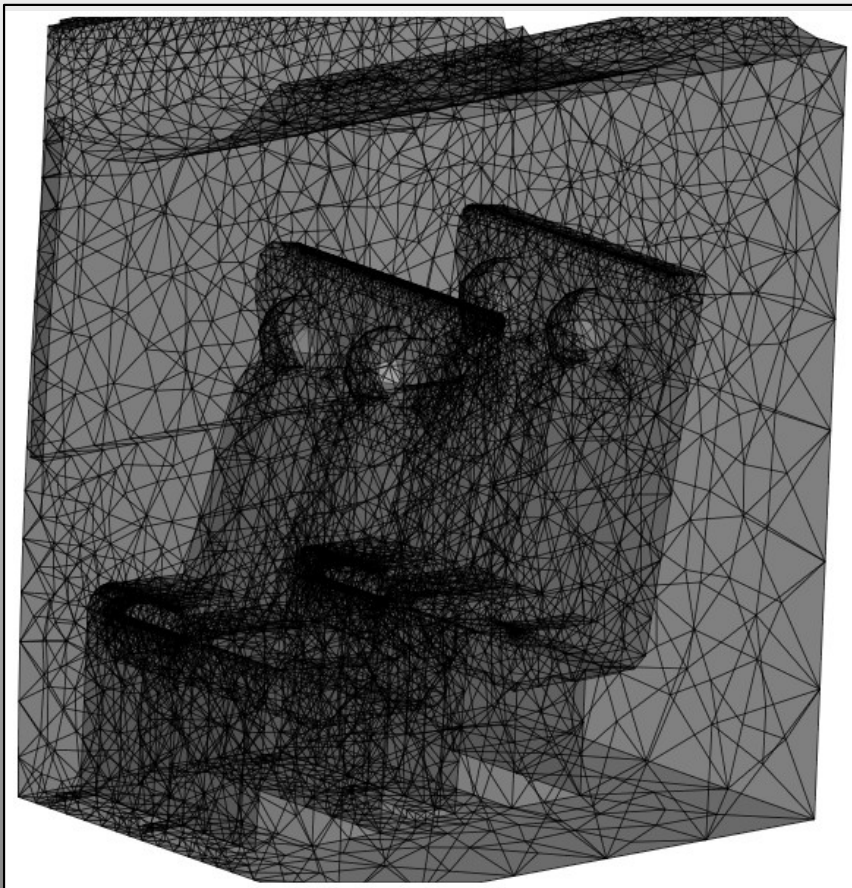
Boundary conditions for thermal analysis:

- ✓ Chosen temperature for incoming air;
- ✓ Chosen heat flux for external confinement of the air volume (both window and lateral wall);
- ✓ Adiabatic condition for symmetry sections, floor and roof of the cabin.



Numerical modeling

Differential equations have been spatially discretized on a no-uniform and no-structured computational grid



- ✓ 360.000 degrees of freedom for the system.
- ✓ Newton-Raphson method for achieving steady solution.
- ✓ Algebraic systems solved by using a direct Unsymmetrical Multi-Frontal method based on the LU decomposition.
- ✓ Computations were carried-out on a 64 bit calculator disposing of 16 GB of RAM.



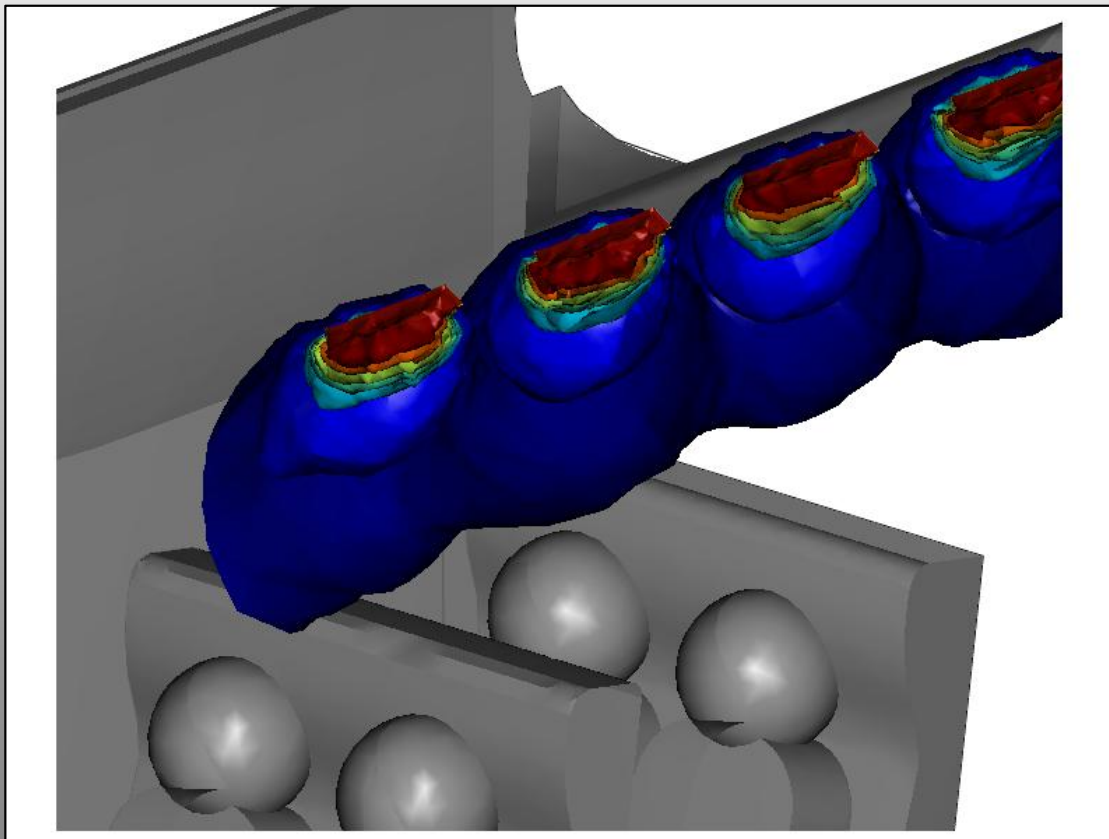
Outlines of presentation

- ✓ Bus-Engineering Company presentation
- ✓ Introduction to “Thermal and Fluid-dynamical comfort”
- ✓ Modeling of a touring bus cabin by COMSOL Multiphysics
- ✓ **Analysis of results**
- ✓ Conclusions & Perspectives



Results

Firstly a **pure ceiling system** for air inlet is studied. This scheme represents a **standard air distribution system, based on the mixing air principle** for indoor conditioning and ventilation.



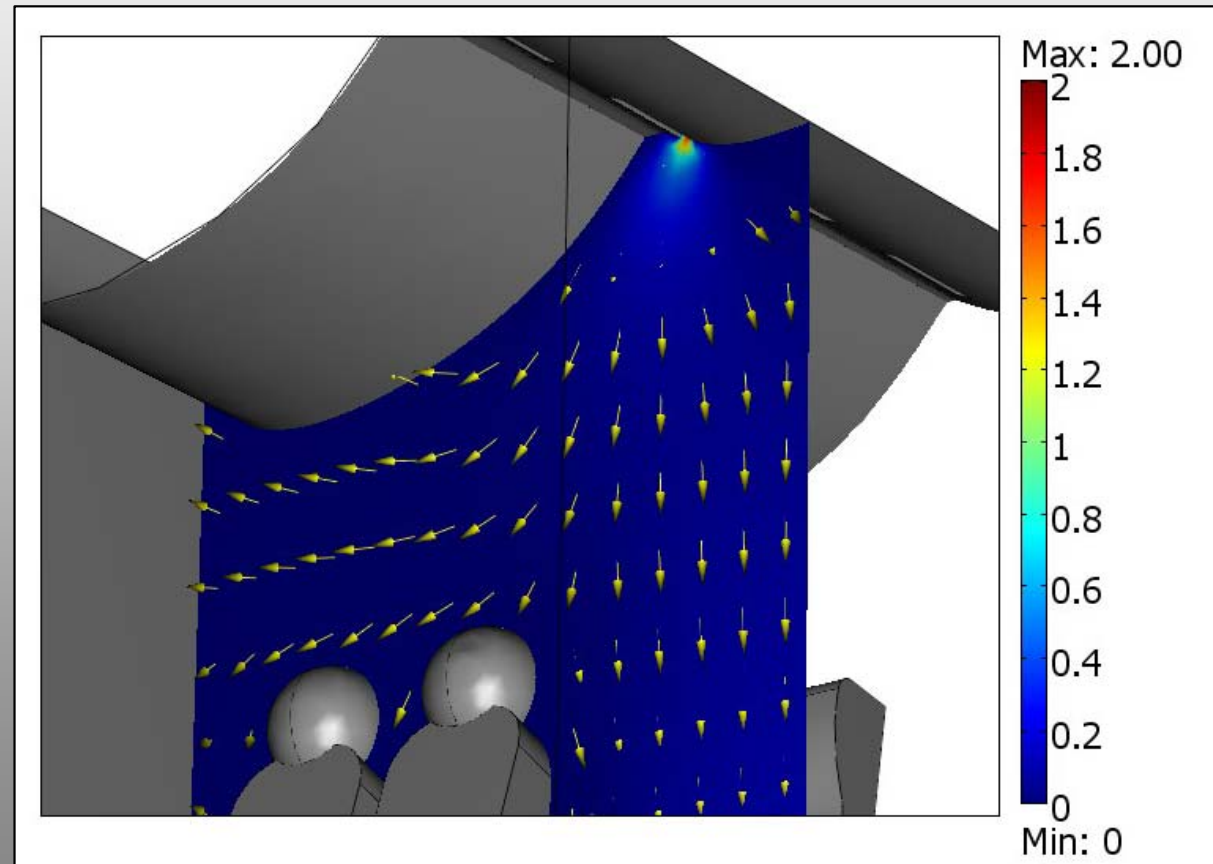
✓ **Ventilation air is provided by 4 rectangular slots** located at the roof in correspondence of the aisle of the bus cabin.



Results

The interest was firstly focused on **verifying passengers comfort referring to the motion field of ventilation air.**

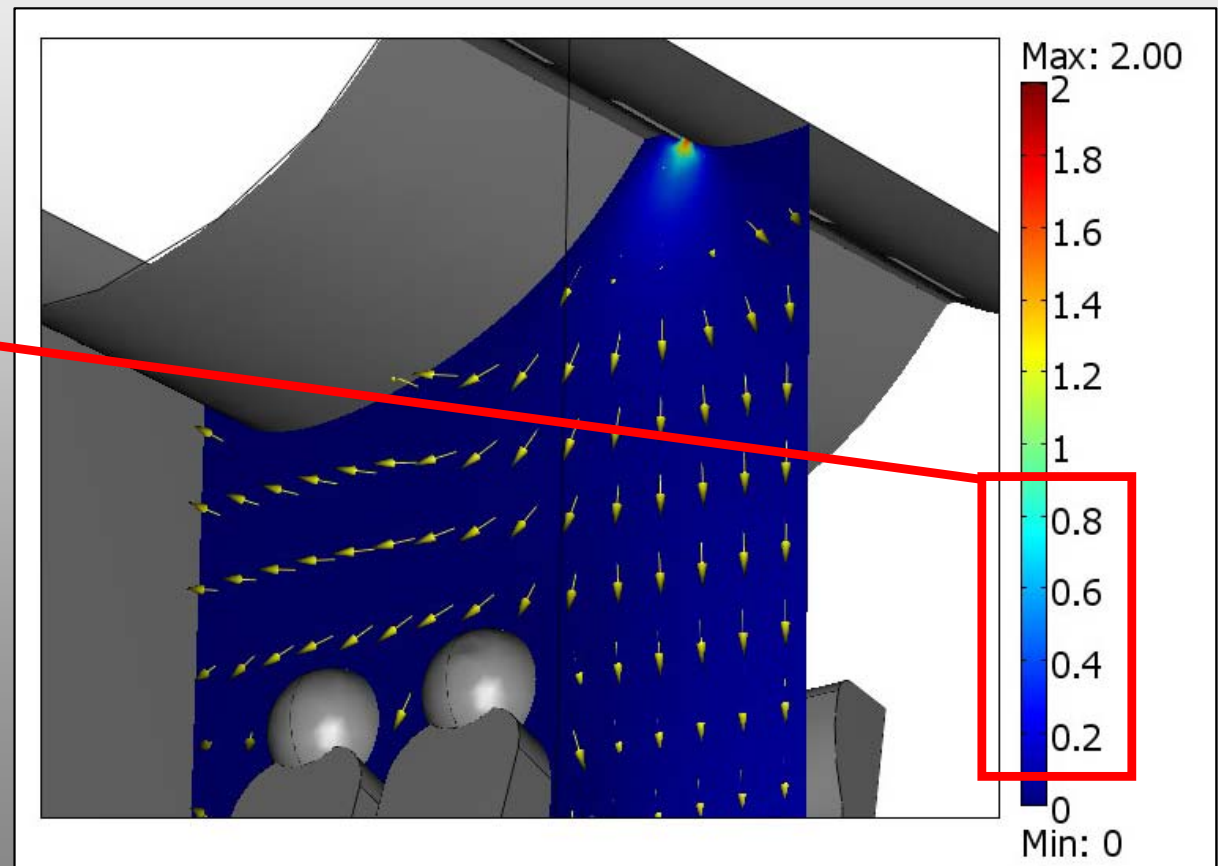
It is recognized that **values of air velocity exceeding 0.8 m/s could be responsible of discomfort condition for human occupants of a ventilated ambient.**



Results

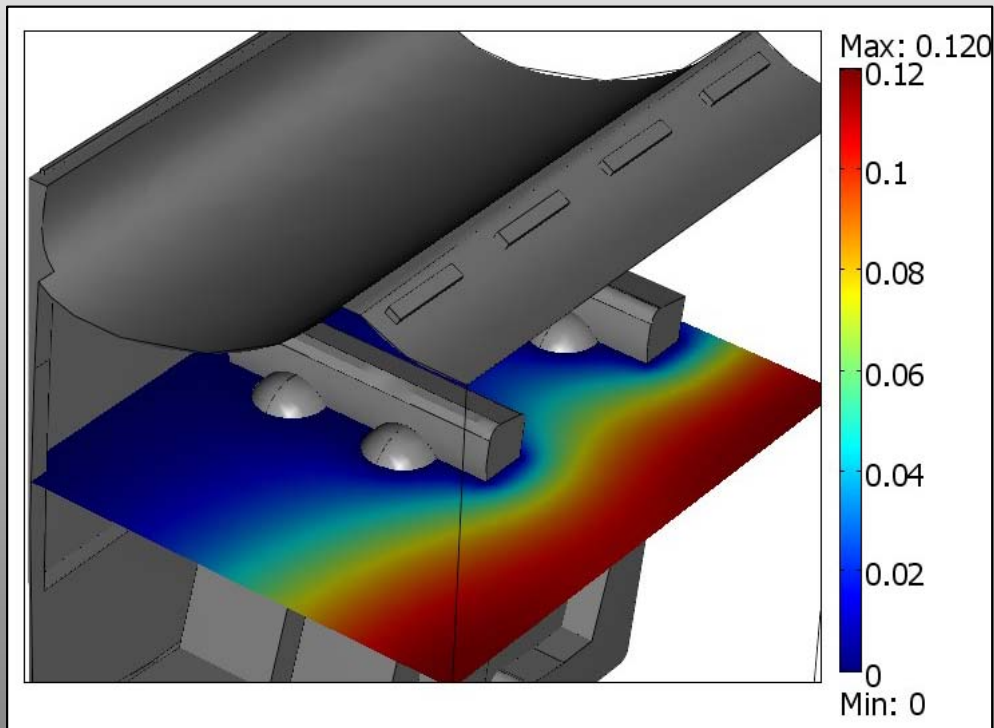
The interest was firstly focused on verifying passengers comfort referring to the motion field of ventilation air.

It is recognized that values of air velocity exceeding **0.8 m/s** could be responsible of discomfort condition for human occupants of a ventilated ambient.



Results

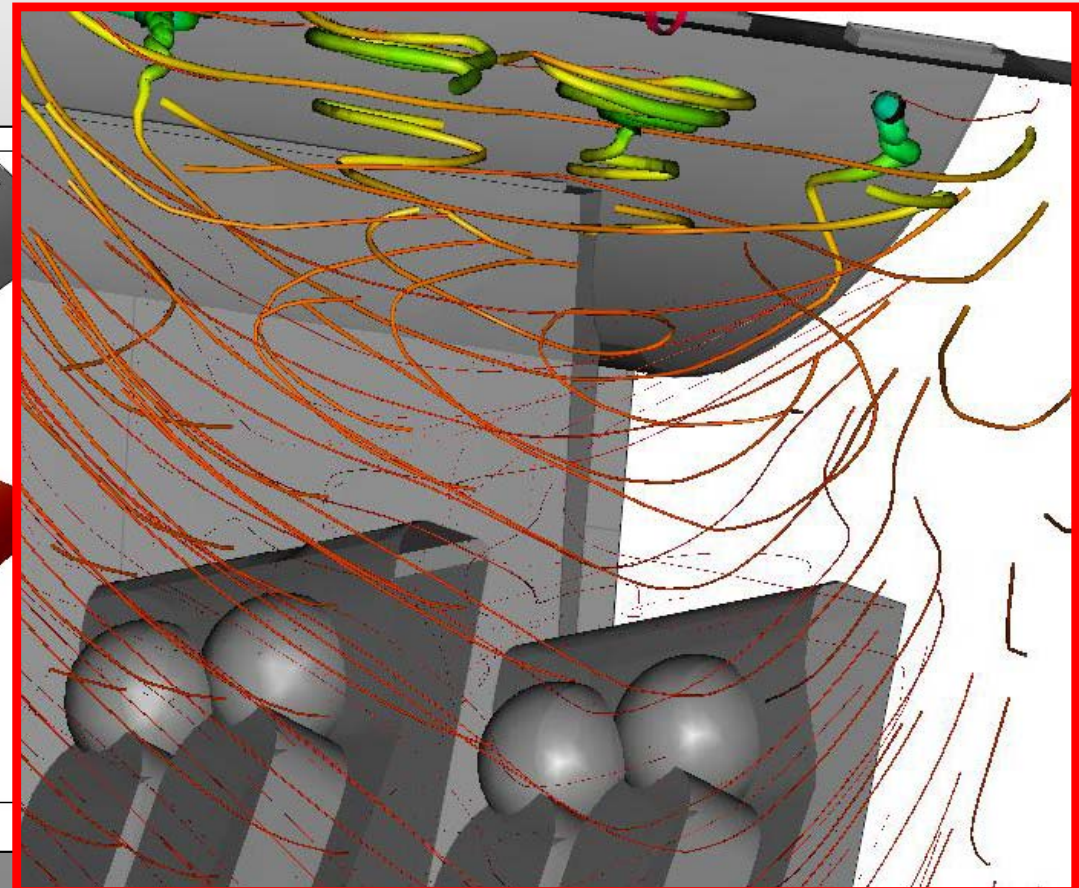
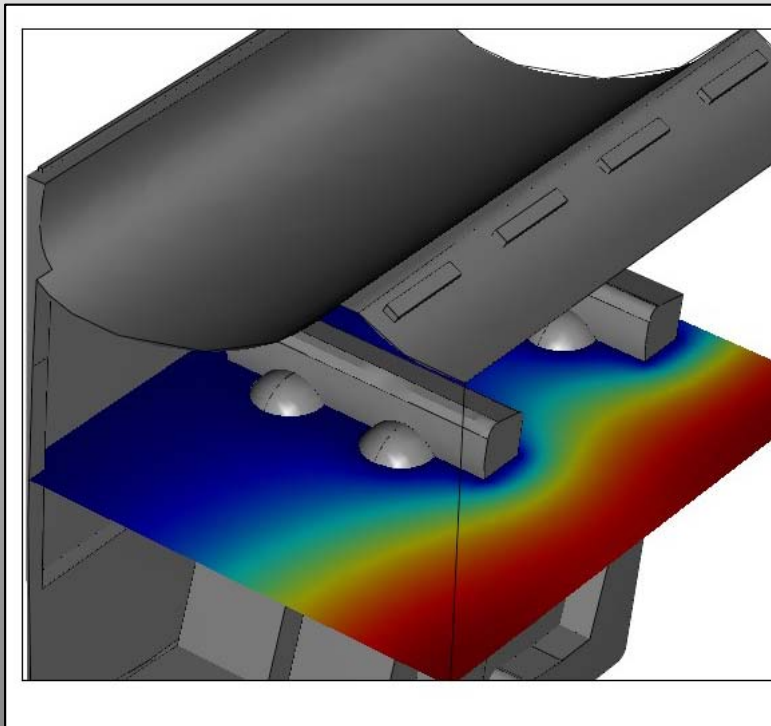
Maximum value of air velocity is reached in a zone not occupied, such as the cabin aisle.



Results

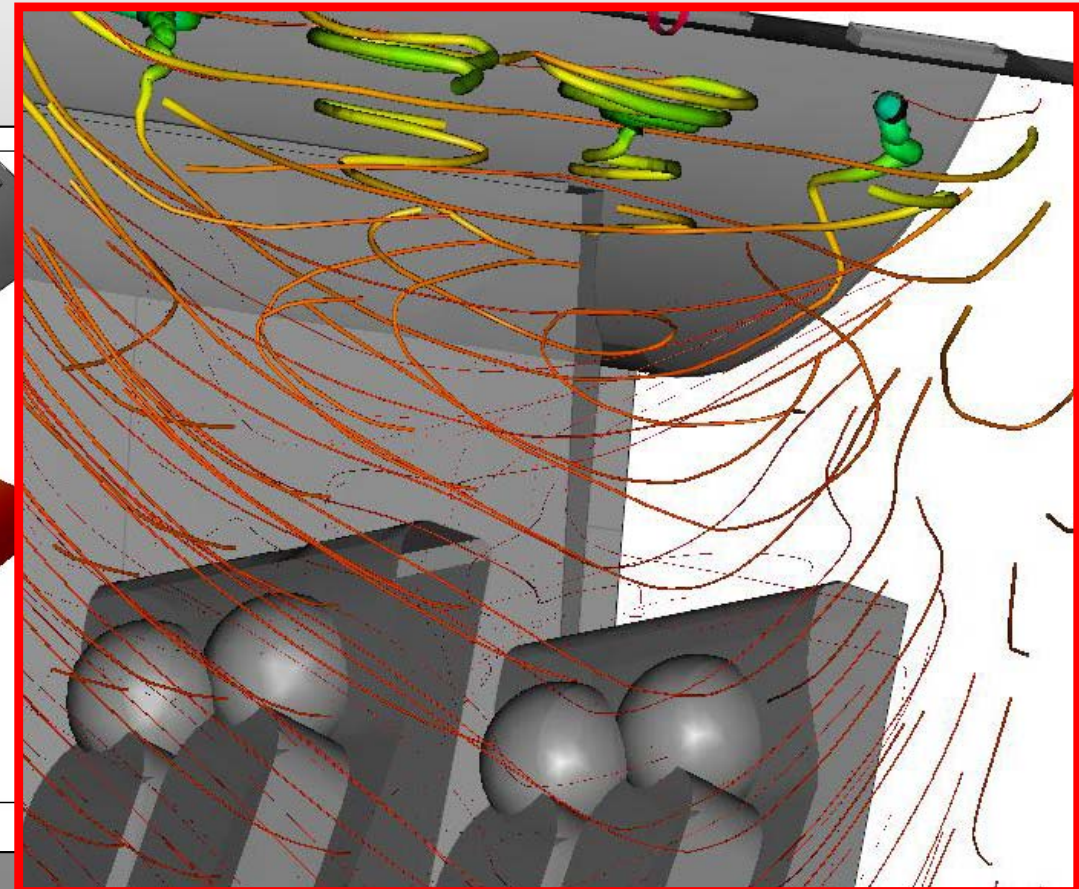
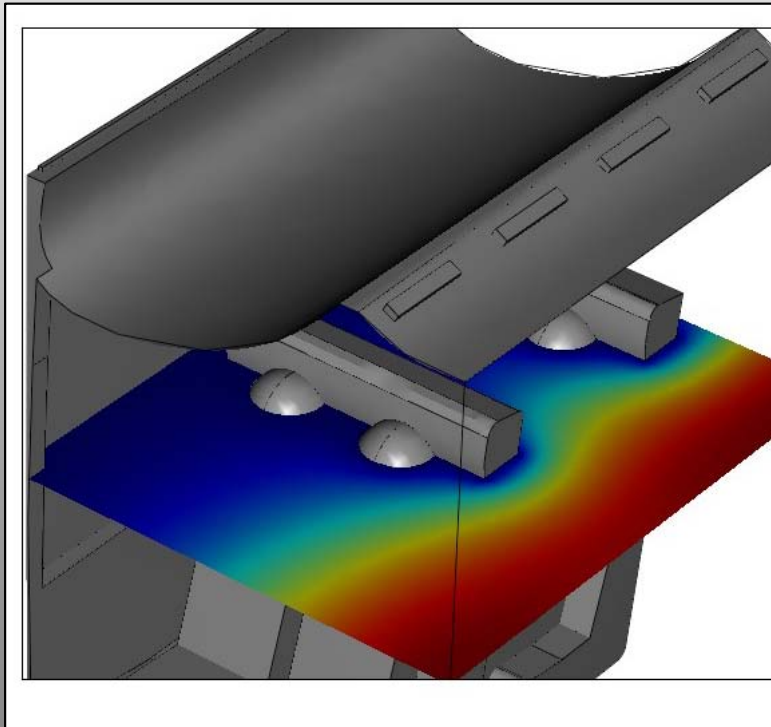
Maximum value of air velocity is reached in a zone not occupied, such as the cabin aisle

High turbulence levels only occur in the top portion of the cabin space



Results

Passengers do not result affected by discomfort due to fluid-dynamical field



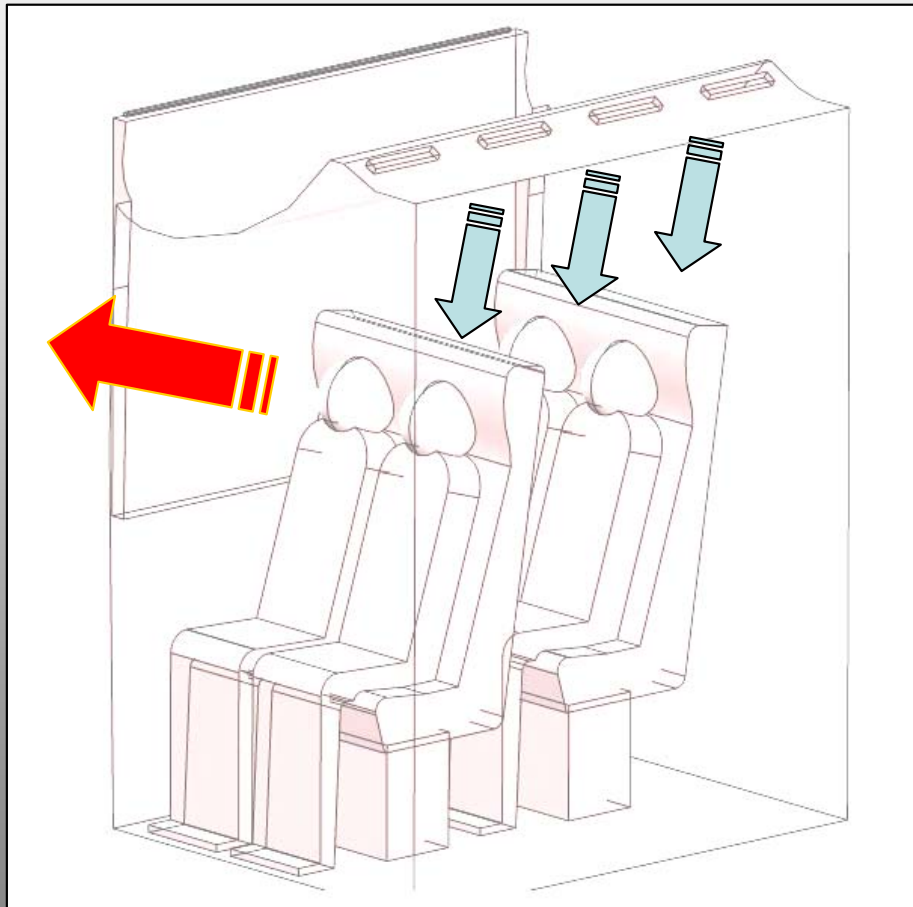


Results

Let now **examine the ceiling air distribution system from a thermal point of view.**

Results

Let now **examine the ceiling air distribution system from a thermal point of view.**



Heating air is introduced from one **lateral side of the passengers seat** close to the cabin aisle.

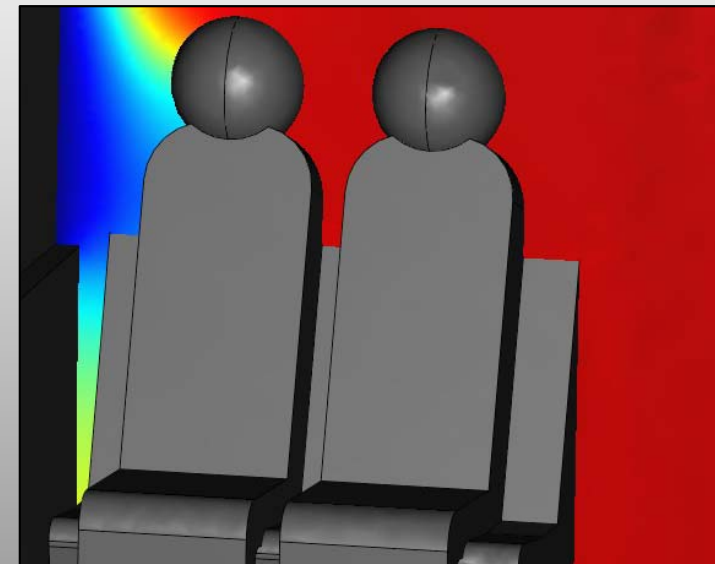
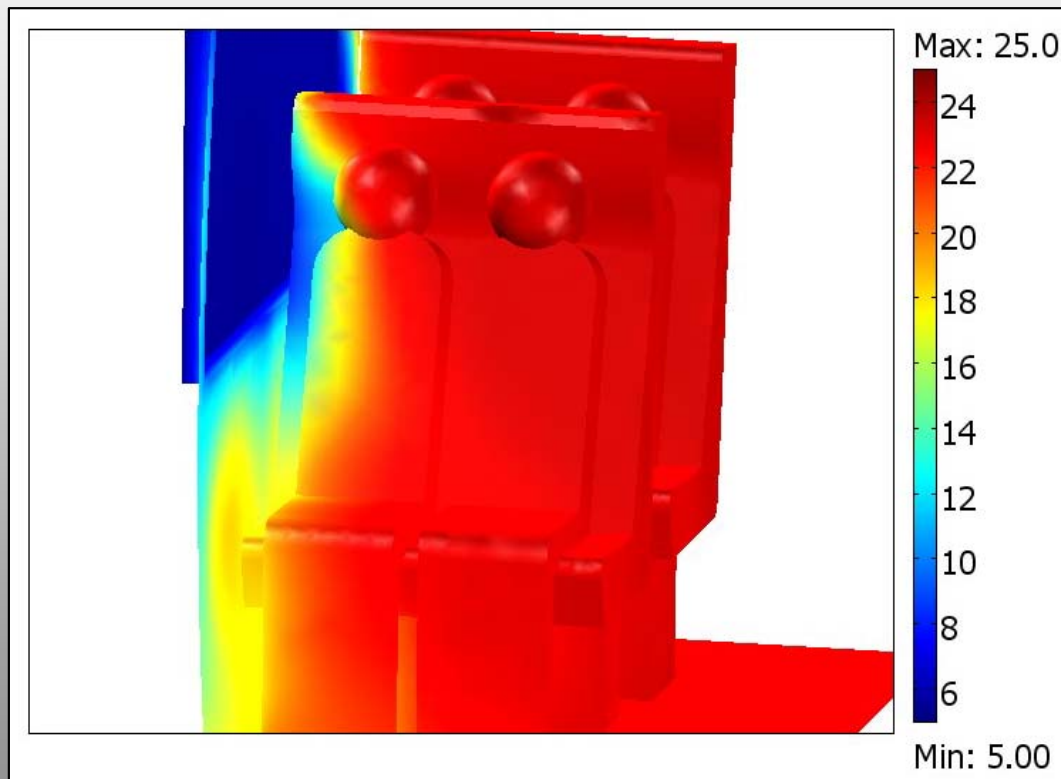
On the other hand, the **higher level of heat dissipation occurs on the opposite side**, close to lateral wall of the bus cabin.

These assumptions let guess to results obtained from thermal analysis...



Results

It is clearly observable as **passengers seated close to the window are submitted to strong temperature gradient** in horizontal direction.





Results

Certainly **the obtained thermal field does not assure thermal comfort** for passengers. Because of that reason **it was simulated a second scheme** for heating air incoming.

This second outline of the numerical model takes its inspiration from the **displacement air conditioning systems**. This system is **based on the opportunity of providing conditioning air from the bottom side of the ambient**, very close to the occupants.



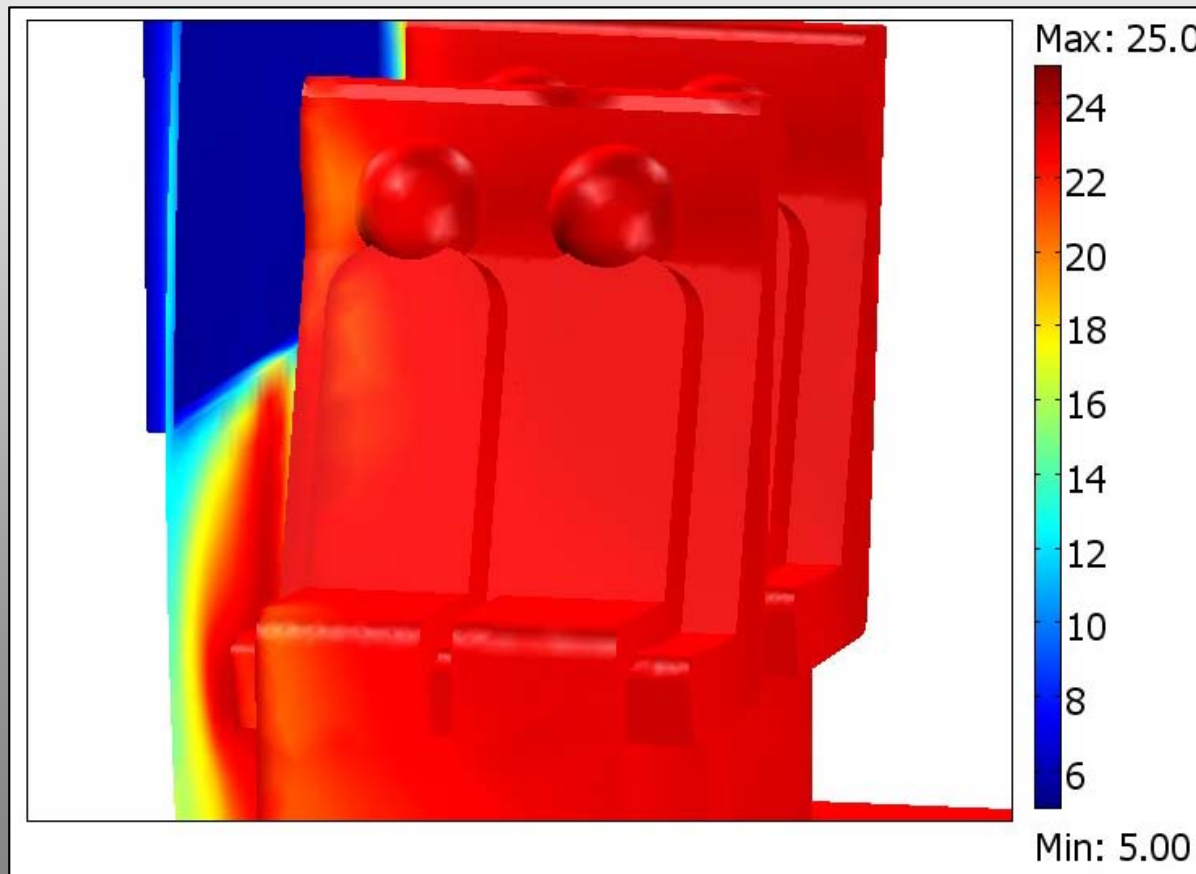
Results

In order to test this layout of inlet section location, **heating air was considered to enter the computational domain through the lateral bottom side of each passenger's seat**

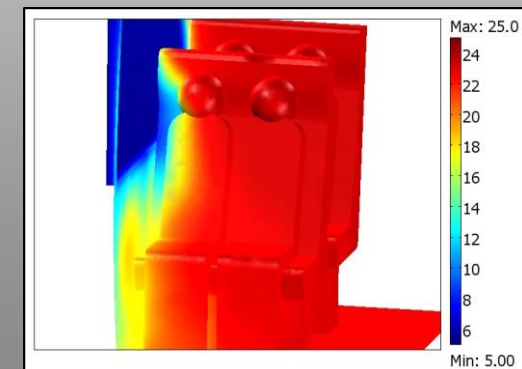


Results

As observable **thermal field at solid-fluid interfaces of the numerical model show an almost uniform distribution of temperature in correspondence of the human occupants.**



That clearly means comfort conditions for passengers.





Outlines of presentation

- ✓ Bus-Engineering Company presentation
- ✓ Introduction to “Thermal and Fluid-dynamical comfort”
- ✓ Modeling of a touring bus cabin by COMSOL Multiphysics
- ✓ Analysis of results
- ✓ **Conclusions & Perspectives**



Conclusions

This study allowed investigating the conditioning air distribution in a touring-bus cabin:

- ✓ **Special attention has been paid to optimise air terminal layout and configuration of inlet section for ventilation air in order to research the best operational scheme assuring high level of comfort for passengers.**
- ✓ **Results have shown as combining a standard ceiling system with a displacement scheme for heating air inlet represents the best compromise guaranteeing thermal comfort for passengers.**



Perspectives

- ✓ Air quality is a complementary factor determining comfort for passengers
- ✓ Work is in progress in order to solve concentration fields for contaminants flowing inside the cabin by coupling transport-diffusion equations to the studied physics



THANK YOU !!!

Bus-Engineering S.r.l. - Viale Africa, 44 - 95129 Catania (I) - Phone/Fax: +39 095 286 4040
Web: <http://www.bus-engineering.it> - E-mail: info@bus-engineering.it

