

Simulating Natural Ventilation Using Boussinesq Approximations (ANSYS Fluent)

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Buoyancy Ventilation In Building

1. Common in building indoor ventilation;
2. Small magnitude comparing to wind driven ventilation;
3. Difficult to identify in a mixed ventilation mode.

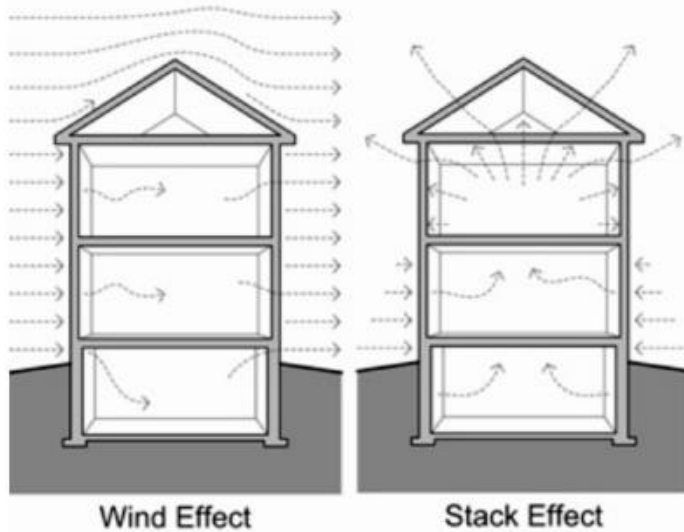
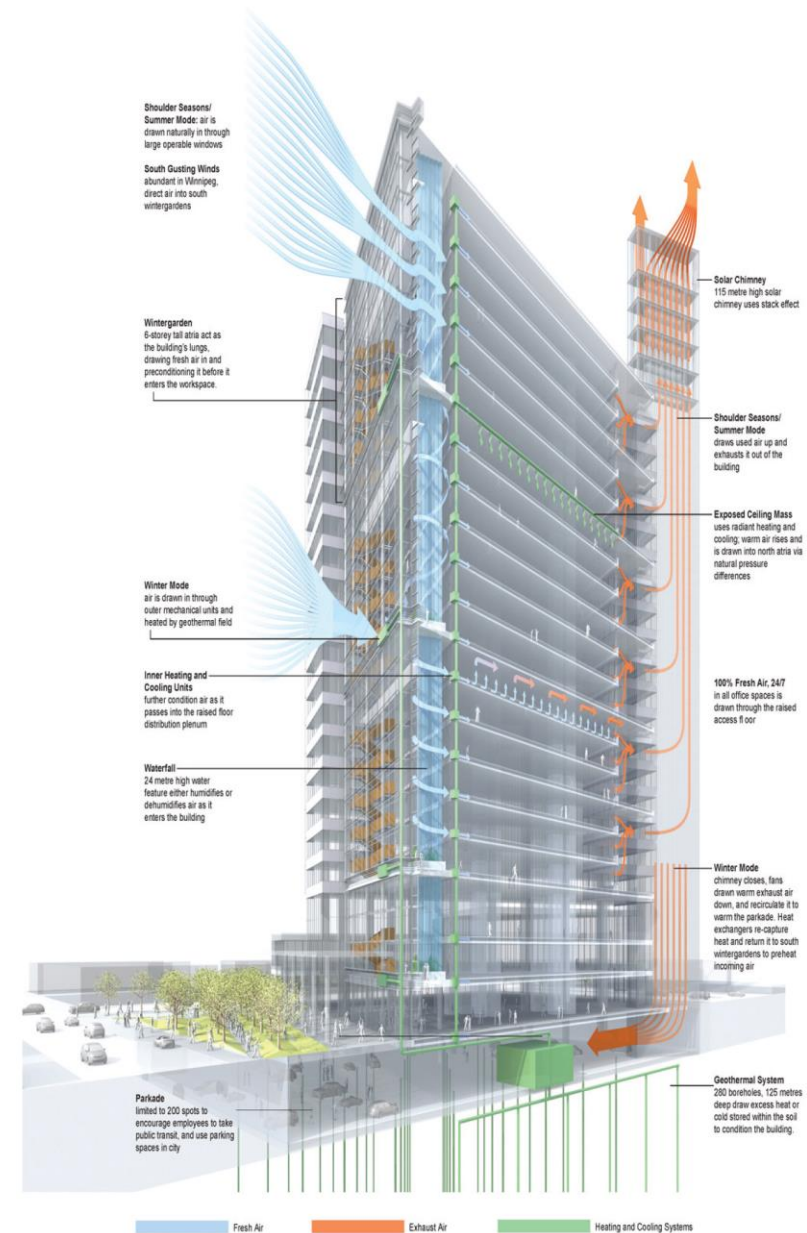


Image from: <https://energy.ces.ncsu.edu/stack-effect-defined/>



Manitoba Hydro Place, Canada

Image from: https://www.hydro.mb.ca/corporate/history/mh_place_design_and_construction/

Boussinesq Approximation

General NS Equations

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \nabla \cdot (\mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I} + \rho \mathbf{g}$$

$$\frac{1}{\rho} \frac{D\rho}{Dt} + \nabla \cdot \mathbf{u} = 0$$

Boussinesq Approximation: “Density variation is only important in the buoyancy term, and can be neglected in the rest of the equation”

(reference: <https://www.comsol.com/multiphysics/boussinesq-approximation>)

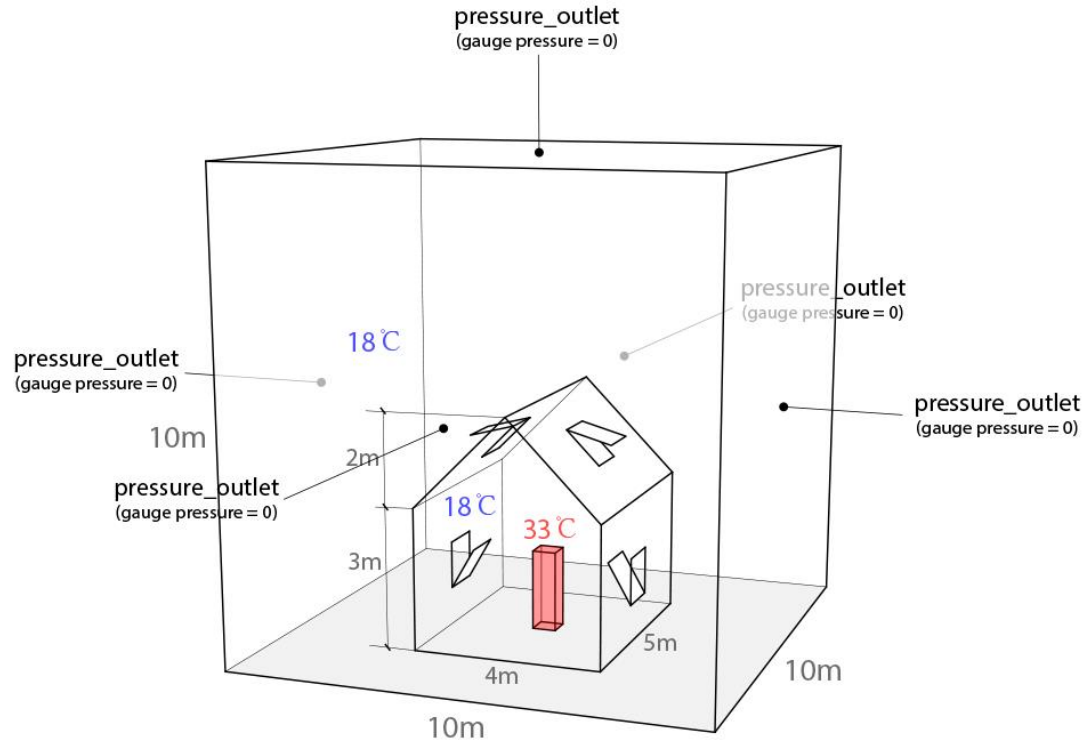
$$\rho_0 \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g} \quad (**\rho_0 \text{ is constant})$$

$$\longrightarrow \rho_0 \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + (\rho_0 + \Delta\rho)\mathbf{g} \quad \Delta\rho = \rho - \rho_0$$

$$(\rho - \rho_0)\mathbf{g} = -\rho_0\beta(T - T_0)\mathbf{g} \quad \text{For ideal gas: } \beta = 1/T_0$$

$$\longrightarrow \rho_0 \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho_0\mathbf{g} - \rho_0(T - T_0)/T_0\mathbf{g}$$

Case Set-up



Geometry:

3D house with hopper windows and roof hatches, one human present in the center of the space.

Physical Environment:

Ambient temperature = 18C;

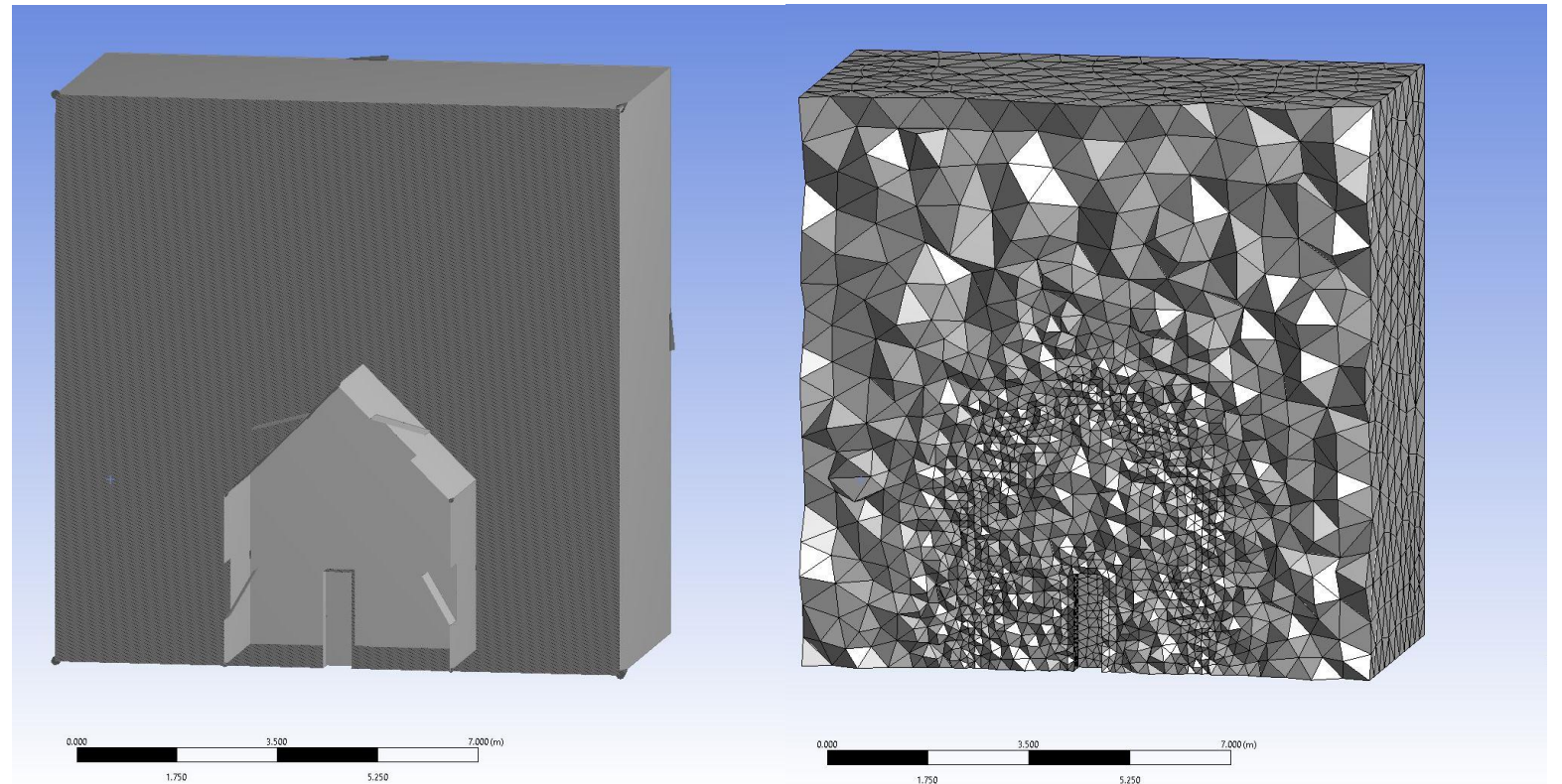
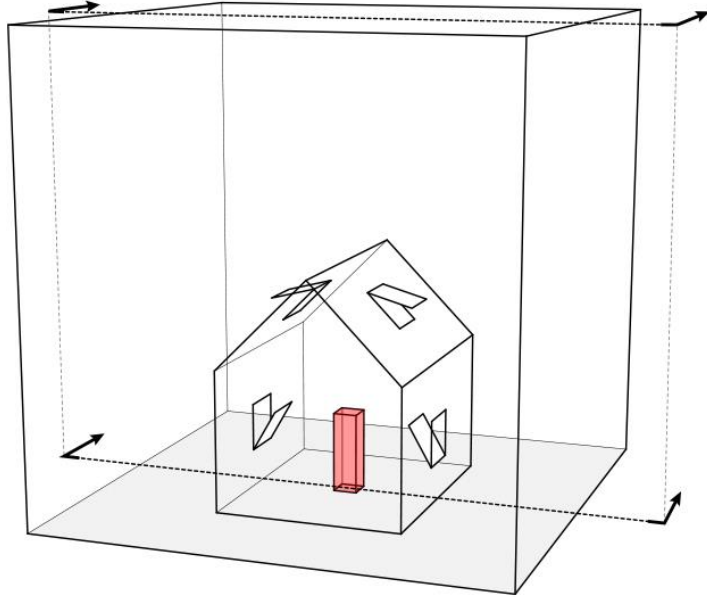
Human skin temperature = 33C.

No velocity inlet (no external force triggering advection).

All open boundary are set as "pressure outlet", with pressure = 0 (back flow will happen)

Meshing

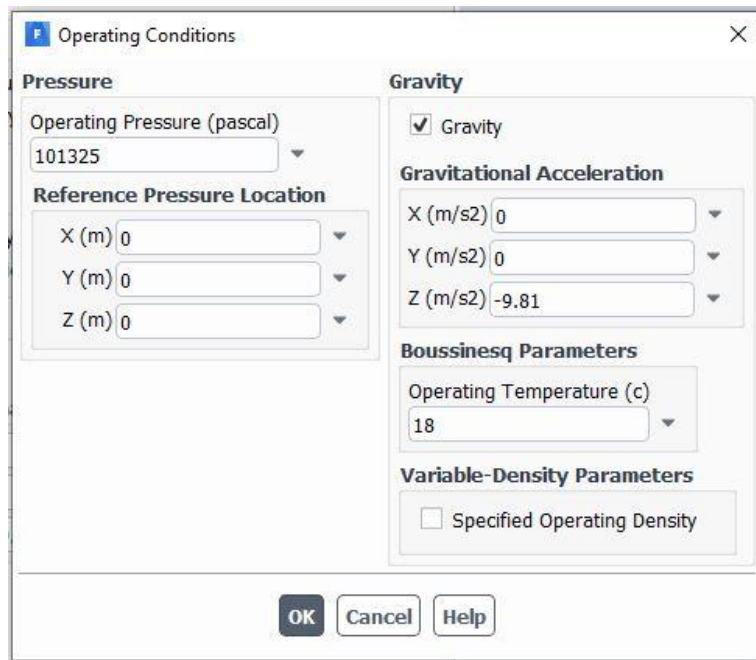
Non-structured Mesh with refined grid size adjacent to walls



Numerical Parameter Setting

Operating Conditions:

1. Gravity
2. Operating Temperature



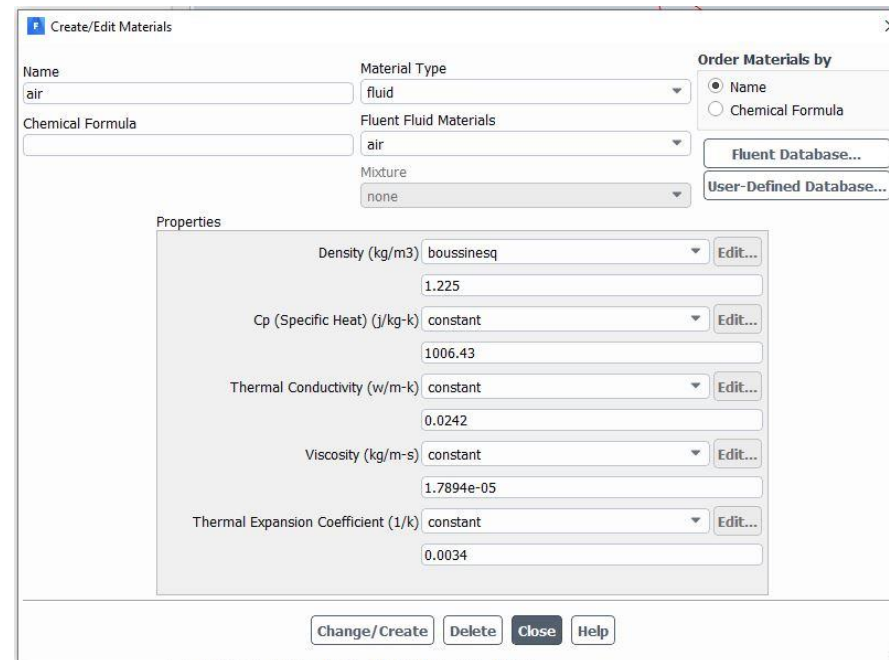
The "Operating Conditions" dialog box is shown. It has two main sections: "Pressure" and "Gravity".

- Pressure:** "Operating Pressure (pascal)" is set to 101325. "Reference Pressure Location" has X (m), Y (m), and Z (m) all set to 0.
- Gravity:** The "Gravity" checkbox is checked. "Gravitational Acceleration" has X (m/s²) at 0, Y (m/s²) at 0, and Z (m/s²) at -9.81. "Boussinesq Parameters" has "Operating Temperature (c)" set to 18. "Variable-Density Parameters" has "Specified Operating Density" unchecked.

Buttons at the bottom: OK, Cancel, Help.

Materials air:

1. Density
2. Thermal Expansion Coefficient



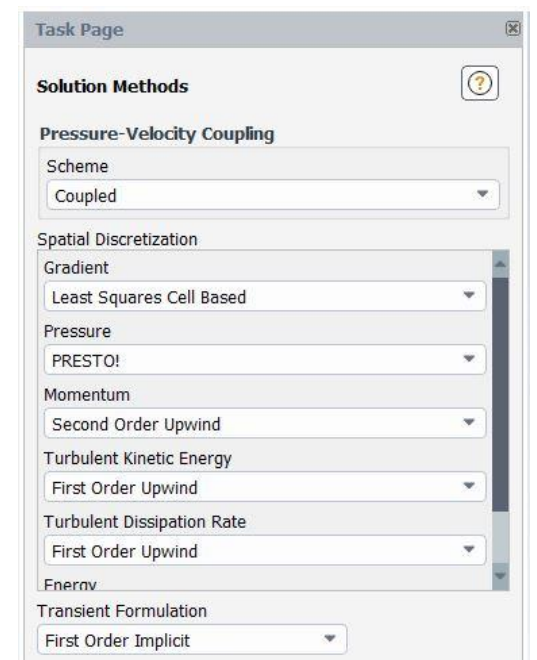
The "Create/Edit Materials" dialog box is shown for the material "air".

- Material Type:** fluid
- Fluent Fluid Materials:** air
- Mixture:** none
- Order Materials by:** Name
- Properties:**
 - Density (kg/m³): boussinesq (dropdown), value: 1.225
 - Cp (Specific Heat) (J/kg-K): constant (dropdown), value: 1006.43
 - Thermal Conductivity (W/m-K): constant (dropdown), value: 0.0242
 - Viscosity (kg/m-s): constant (dropdown), value: 1.7894e-05
 - Thermal Expansion Coefficient (1/K): constant (dropdown), value: 0.0034

Buttons at the bottom: Change/Create, Delete, Close, Help.

Solution Methods:

Pressure: PRESTO!



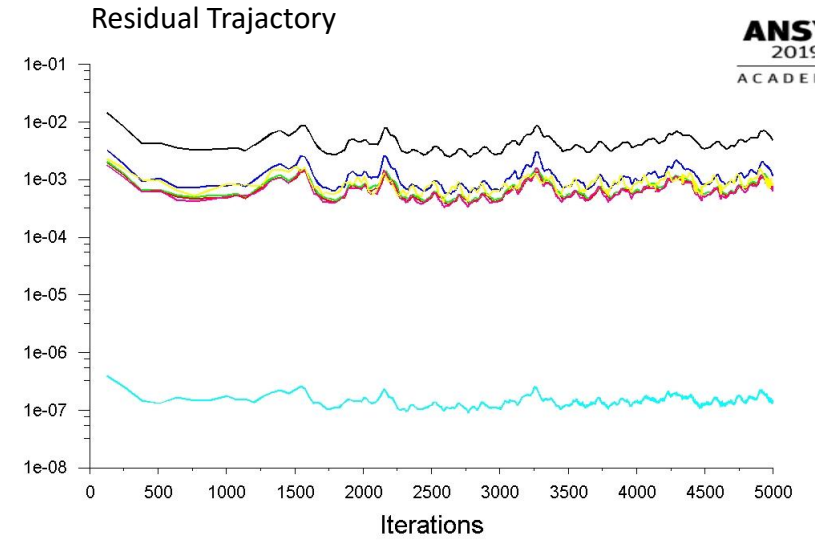
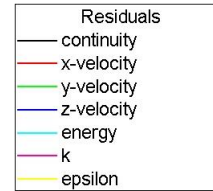
The "Task Page" dialog box is shown, displaying solution methods for the "Pressure" variable.

- Solution Methods:** Pressure-Velocity Coupling: Coupled (dropdown)
- Spatial Discretization:** Gradient: Least Squares Cell Based (dropdown)
- Pressure:** PRESTO! (dropdown)
- Momentum:** Second Order Upwind (dropdown)
- Turbulent Kinetic Energy:** First Order Upwind (dropdown)
- Turbulent Dissipation Rate:** First Order Upwind (dropdown)
- Energy:** Transient Formulation: First Order Implicit (dropdown)

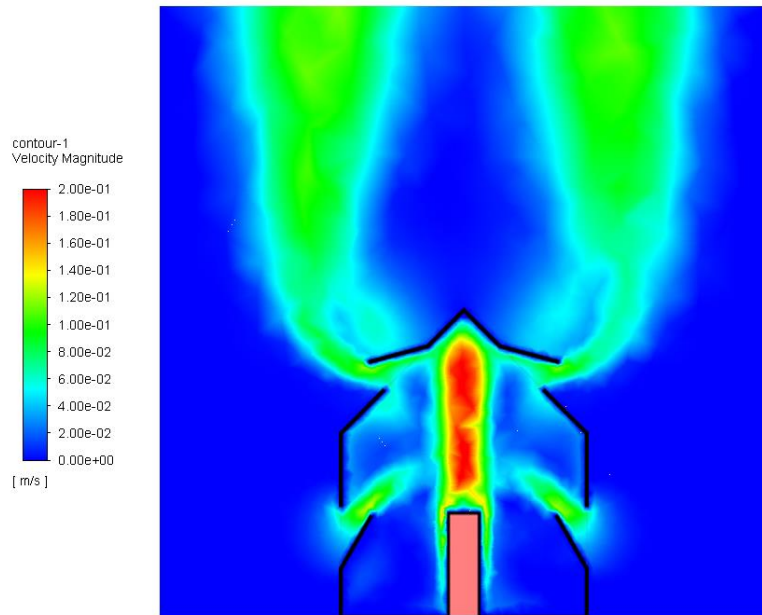
"PRESTO! (PREssure STaggering Option) scheme uses the discrete continuity balance for a "staggered" control volume about the face to compute the "staggered" (i.e., face) pressure." (Reference: <https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node371.htm>)

Steady State Simulation Result

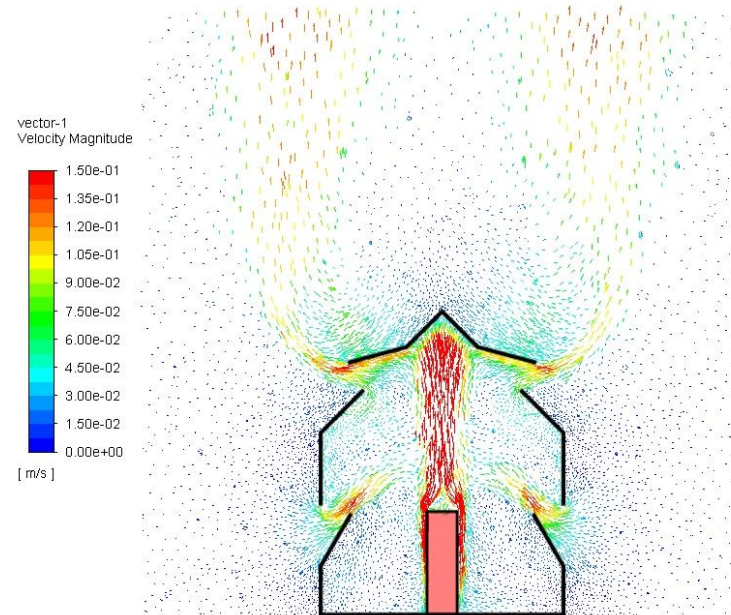
Total No. of iterations = 5000



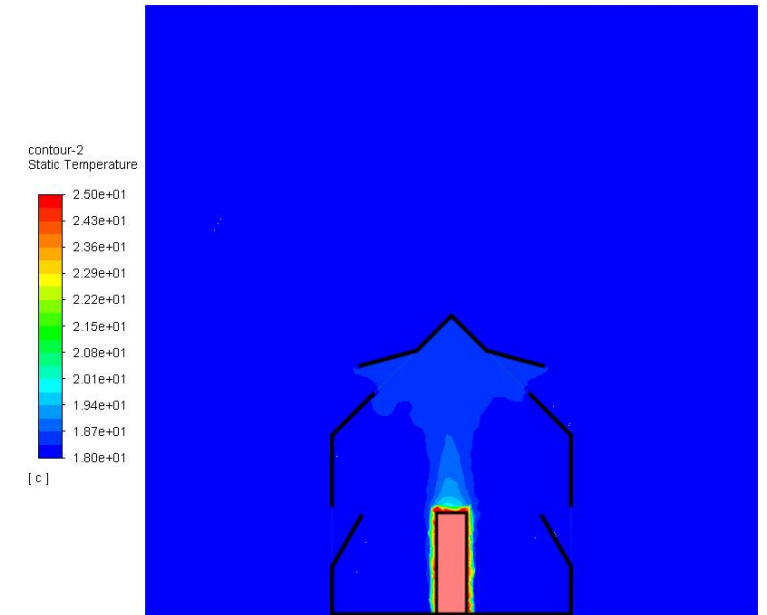
Velocity Magnitude



Velocity vector



Temperature



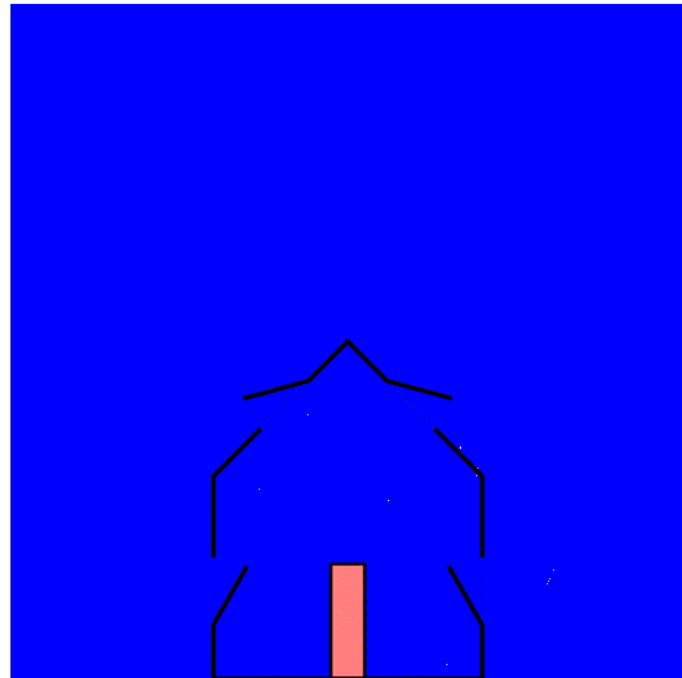
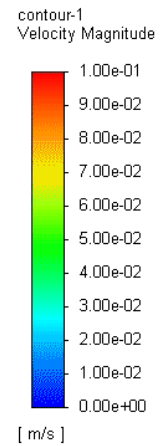
Transient Simulation Result

Time step = 0.1s;

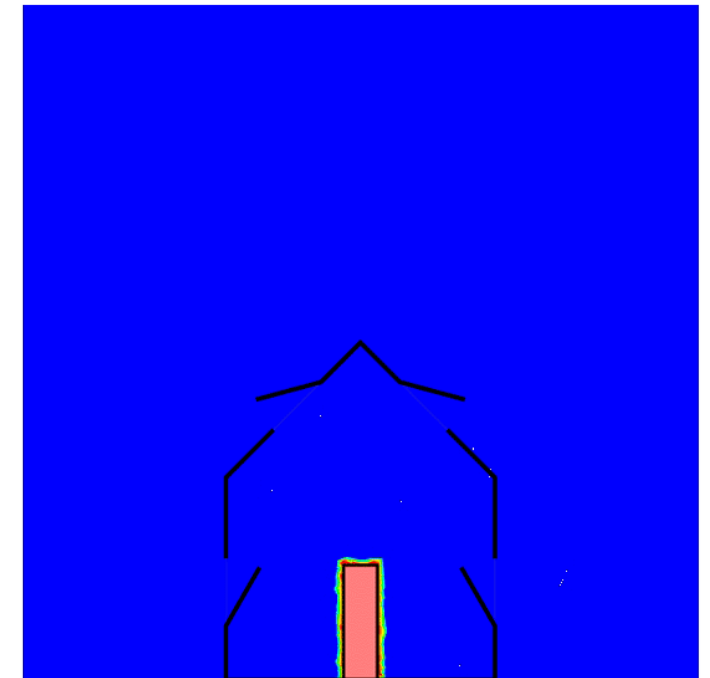
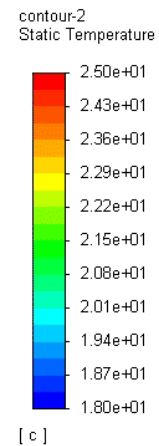
Total No. of time steps = 1000

Max CFL ~ 1 (can be greater than 1)

Velocity Magnitude

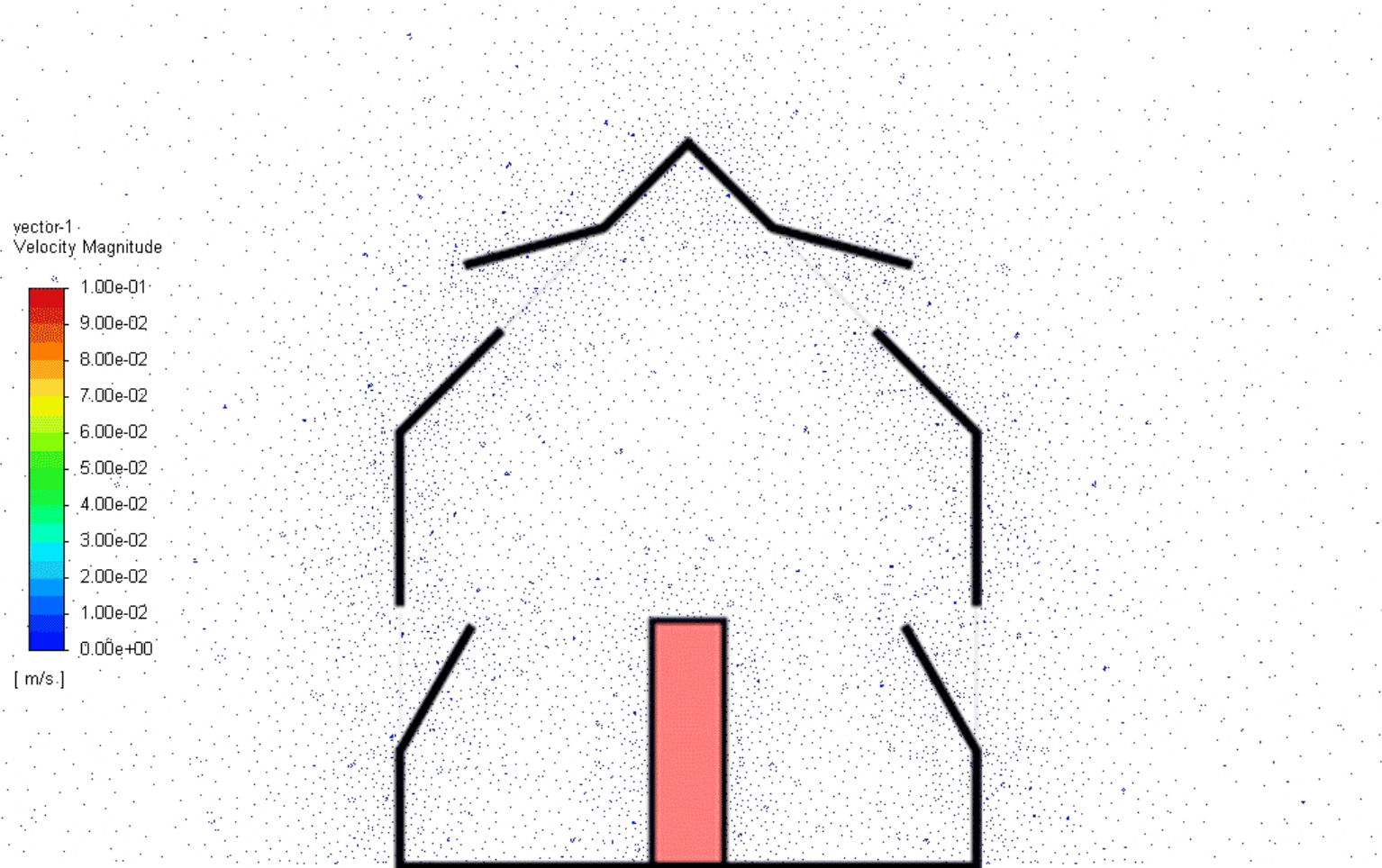


Temperature



Transient Simulation Result

Velocity vector



Conclusion & Discussion

1. Boussinesq approximation is robust in calculating weak buoyancy driven flow like building interior stack effect;
2. In this situation, pressure outlet boundary condition with gauge pressure=0 can be used in absence of a velocity/ pressure inlet (back flow will happen);
3. The residual for most of the variables fluctuate around 10^{-3} (continuity $\sim 10^{-2}$), further improvement could be tested:
 - a. Reduce dt and dx;
 - b. Optimize mesh (e.g. inflation layers at walls)