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.

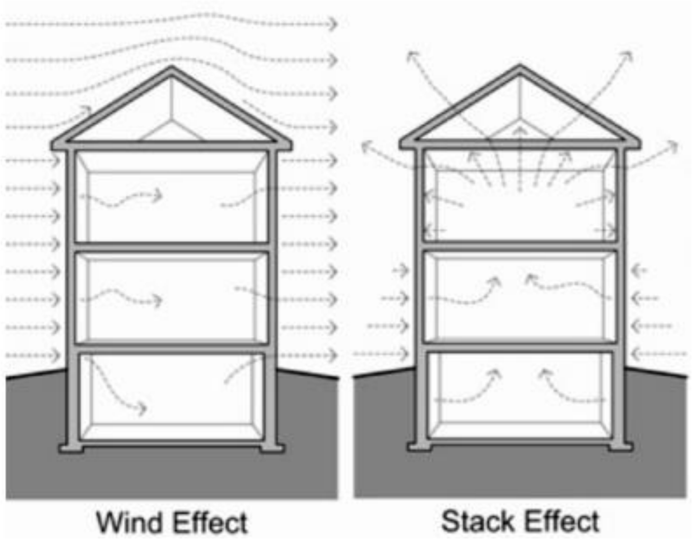
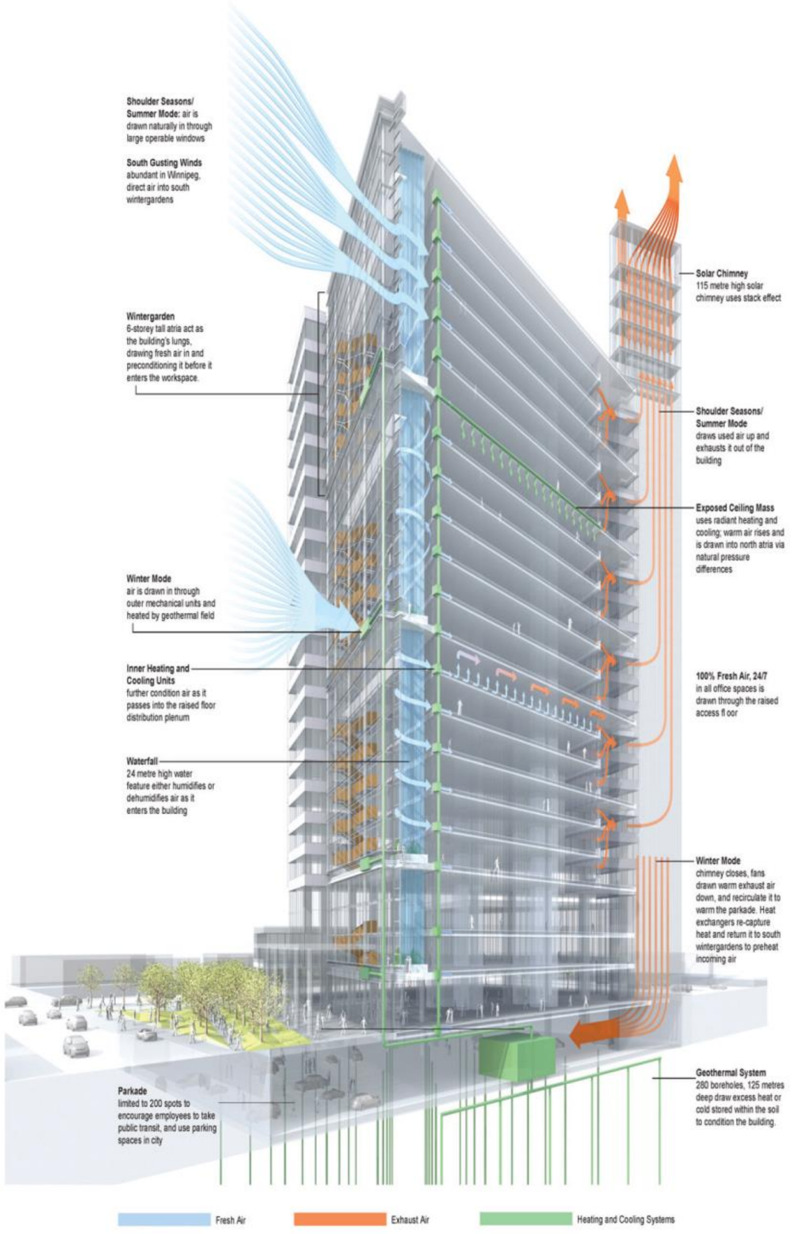


Image from: https://energy.ces.ncsu.edu/stack-effect-defined/



Manitoba Hydro Place, Canada

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

Boussinesq Approximation

General NS Equations

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

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

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)

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

(**ρ0 is constant)

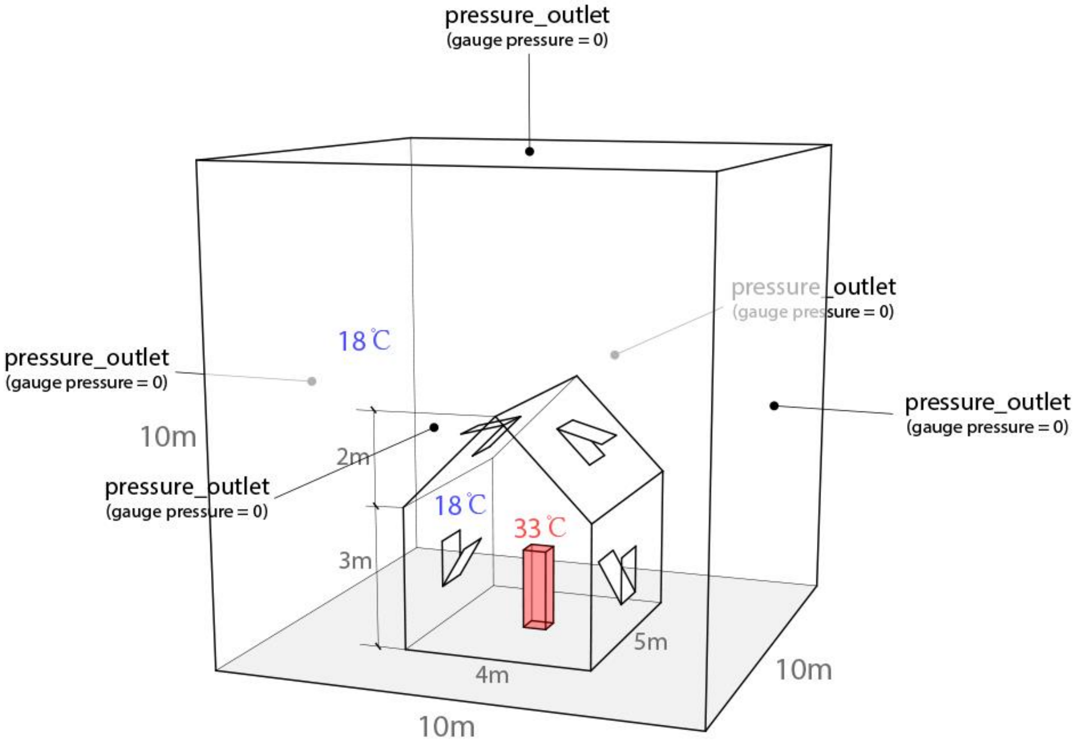
$$\longrightarrow\quad \rho_0\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mu\nabla^2\mathbf{u}+(\rho_0+\Delta\rho)\mathbf{g}\qquad \Delta\rho=\rho-\rho_0$$

$$(\rho-\rho_0)\mathbf{g}=-\rho_0\beta(T-T_0)\mathbf{g}$$

For ideal gas: $\beta=1/T_0$

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

Case Set-up



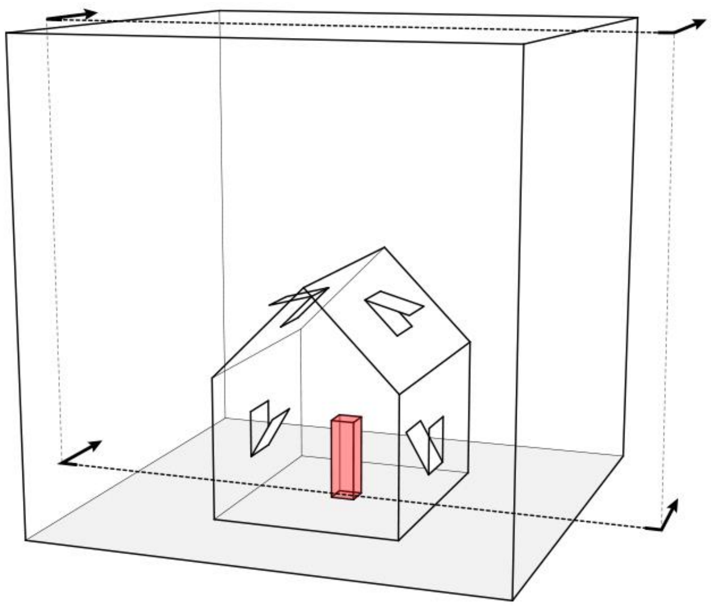
Geometry:
3D house with hopper windows and roof hatches, one human present in the center of the space.

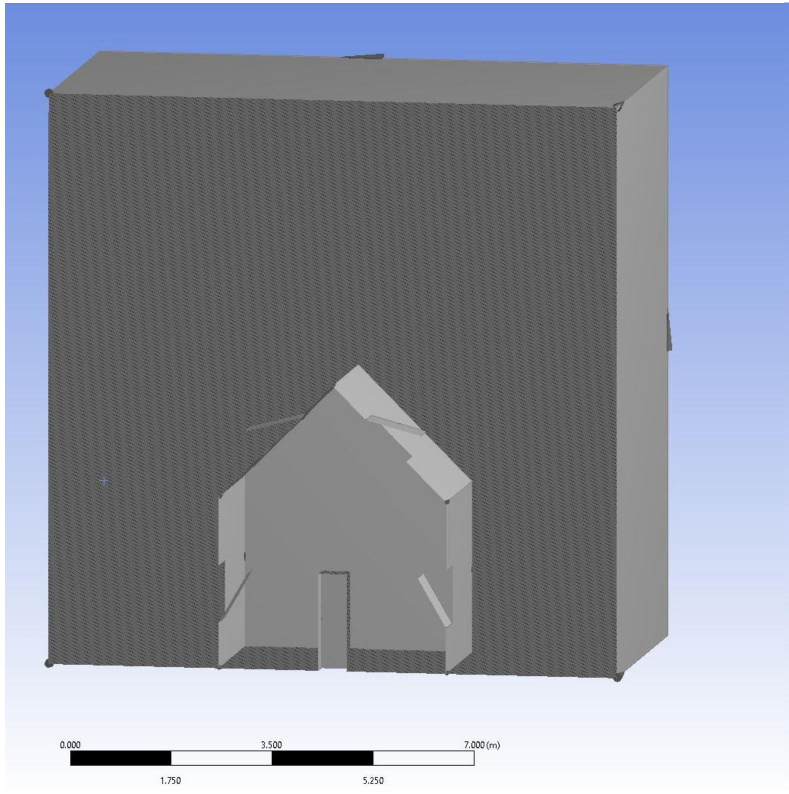
Physical Environment:
Ambient temperature =18C;
Human skin temperature = 33C.

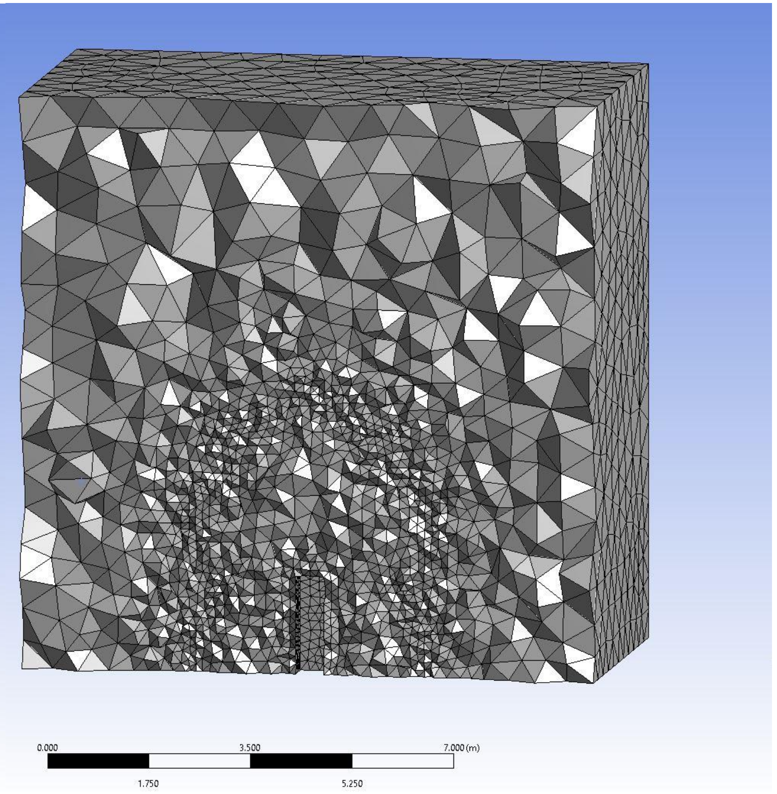
No velocity inlet (no external force triggering advection).
All open boundary are set as “pressure outlet”, with pressure = 0 (back flow will happen)

Meshing

Non-structured Mesh with refined grid size adjacent to walls

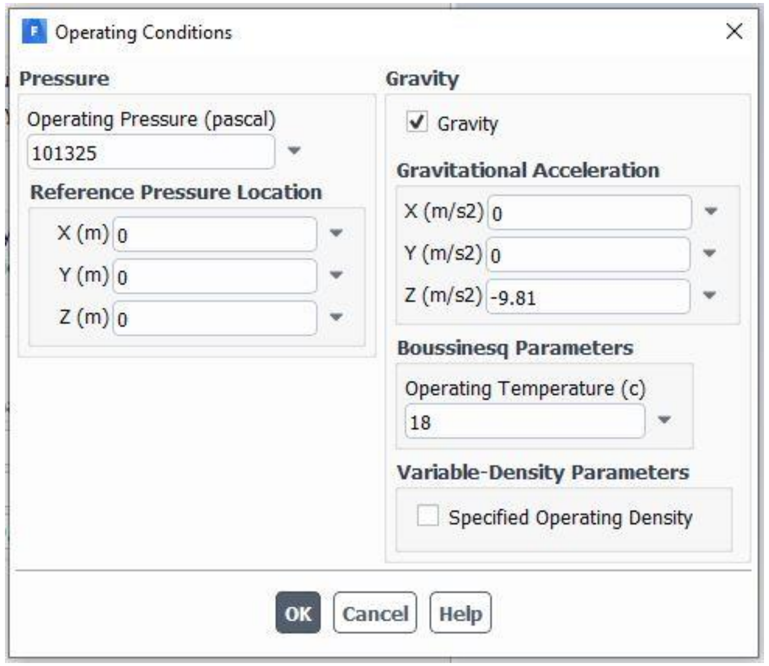




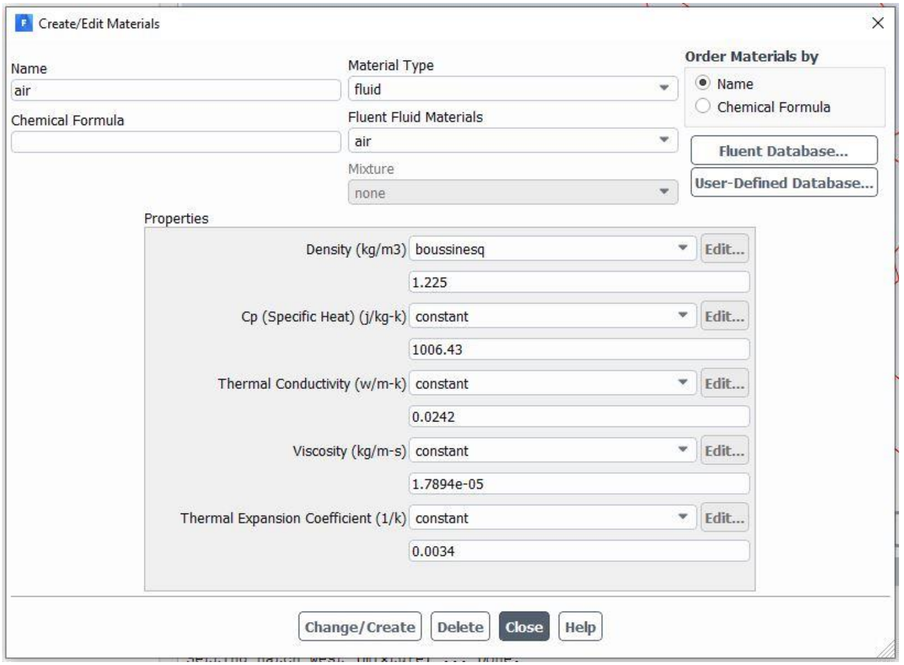


Numerical Parameter Setting

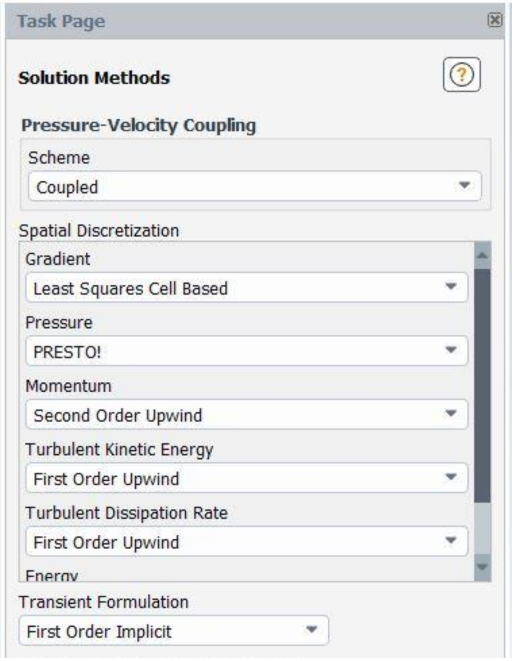
Operating Conditions:
1. Gravity 2. Operating Temperature



Materials air:
1. Density 2. Thermal Expansion Coefficient



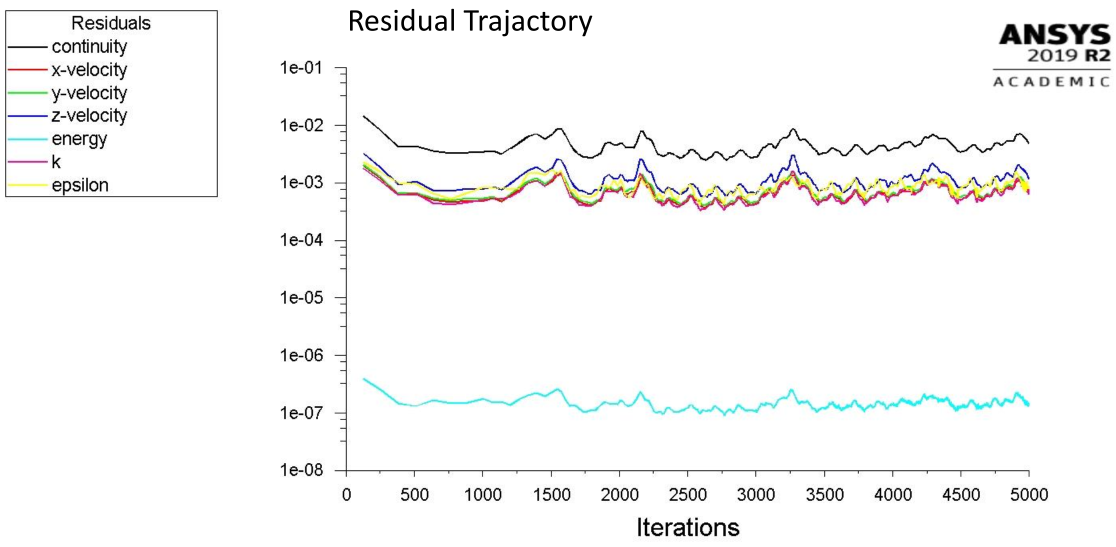
Solution Methods:
Pressure: PRESTO!



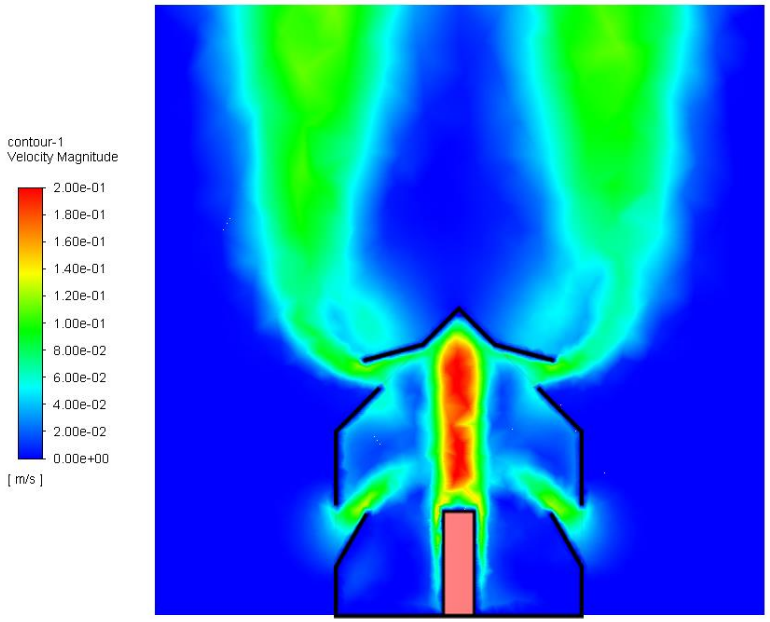
“PRESTO! (PREssure STaggering Option) scheme uses the discrete continuity balance for a "staggered'' control volume about the face to compute the "staggered'' (i.e., face) pressure.” (Reference: https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node371.htm)

Steady State Simulation Result

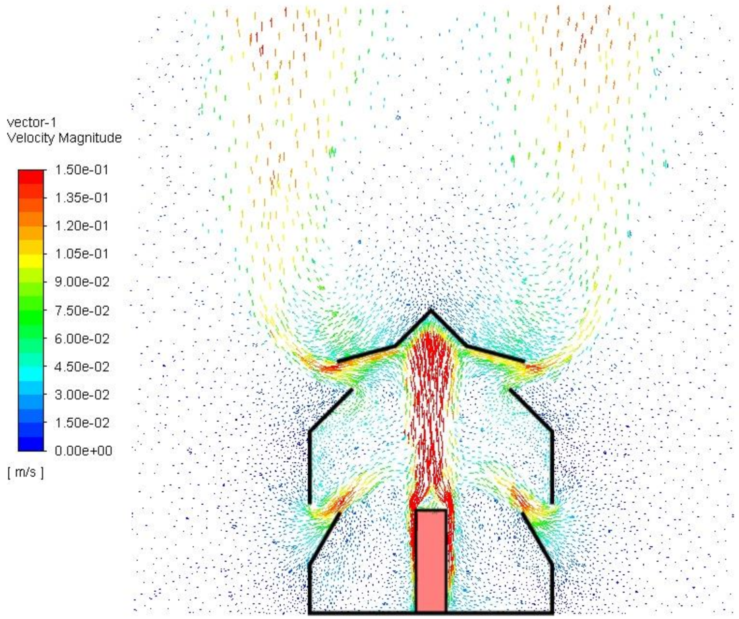
Total No. of iterations = 5000



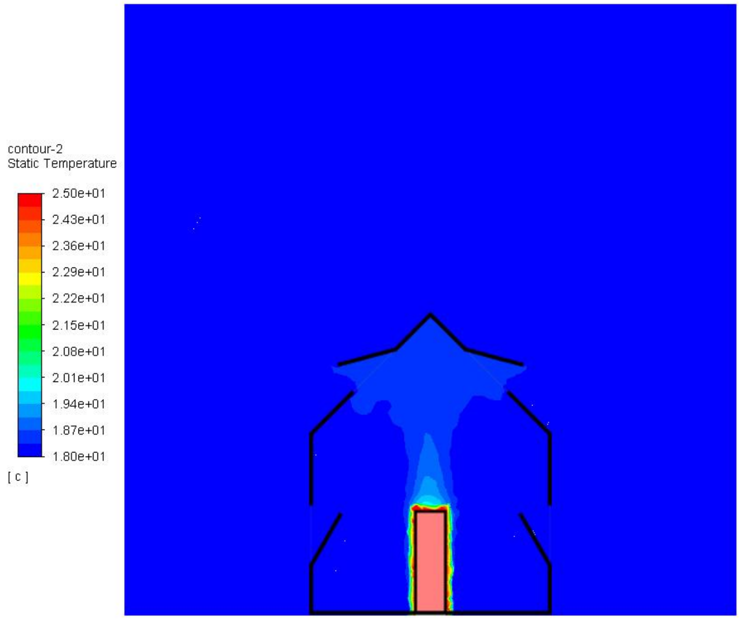
Velocity Magnitude



Velocity vector



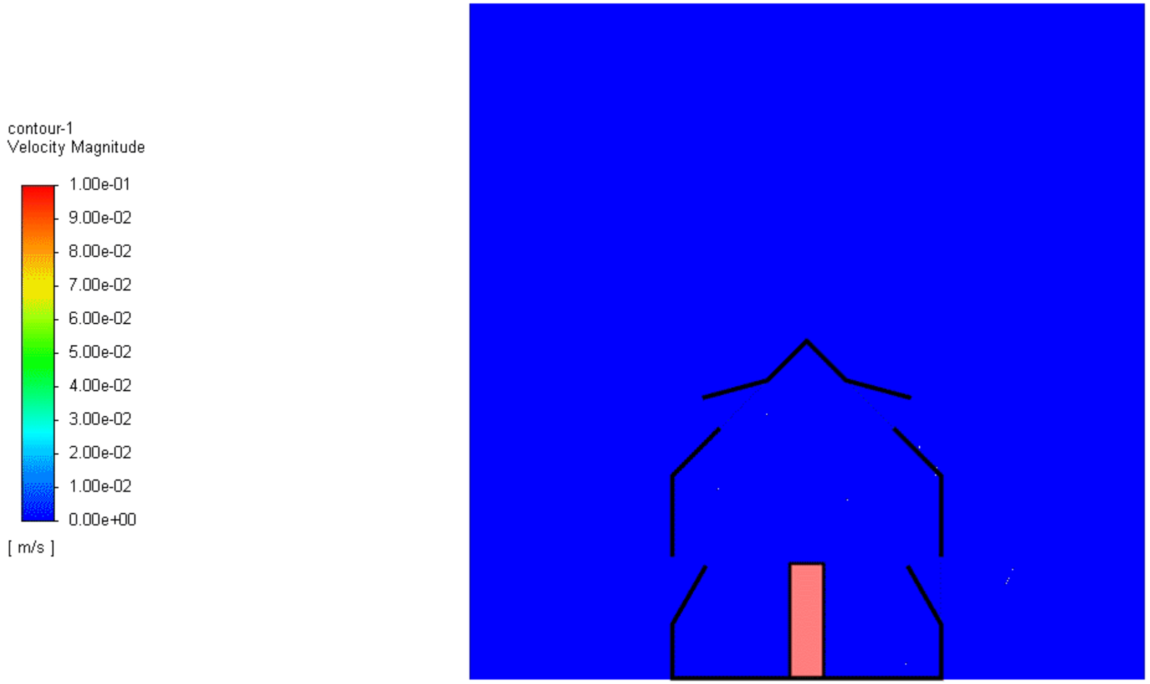
Temperature



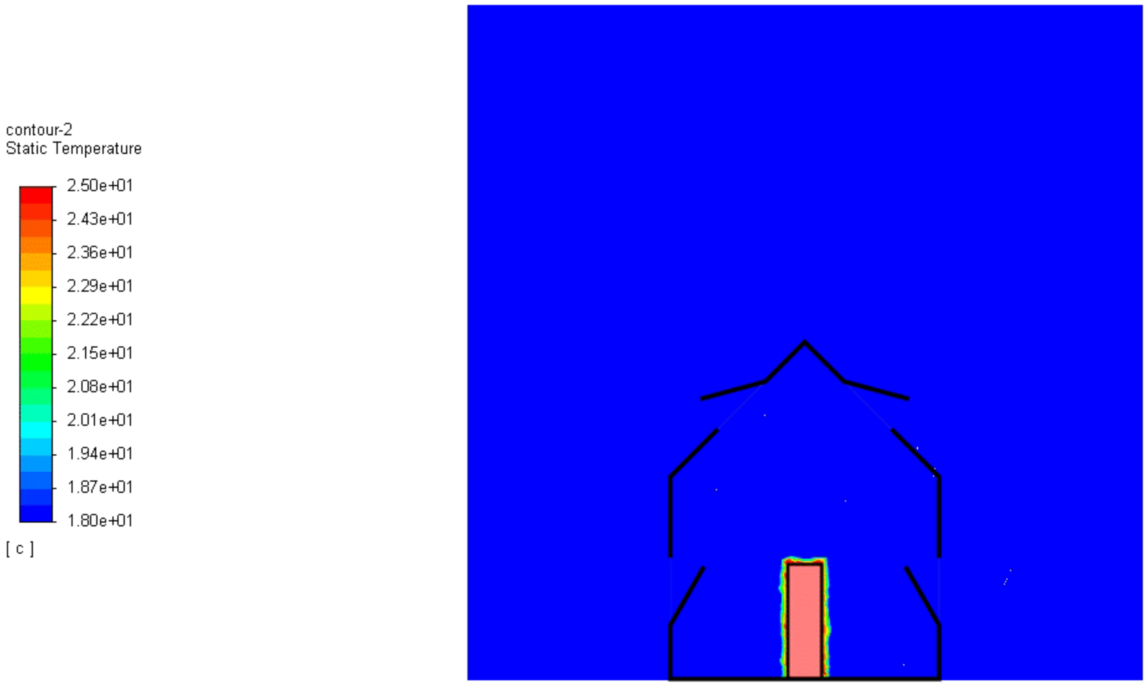
Transient Simulation Result

Time step = 0.1s;
Total No. of time steps = 1000
Max CFL ~ 1 (can be greater than 1)

Velocity Magnitude

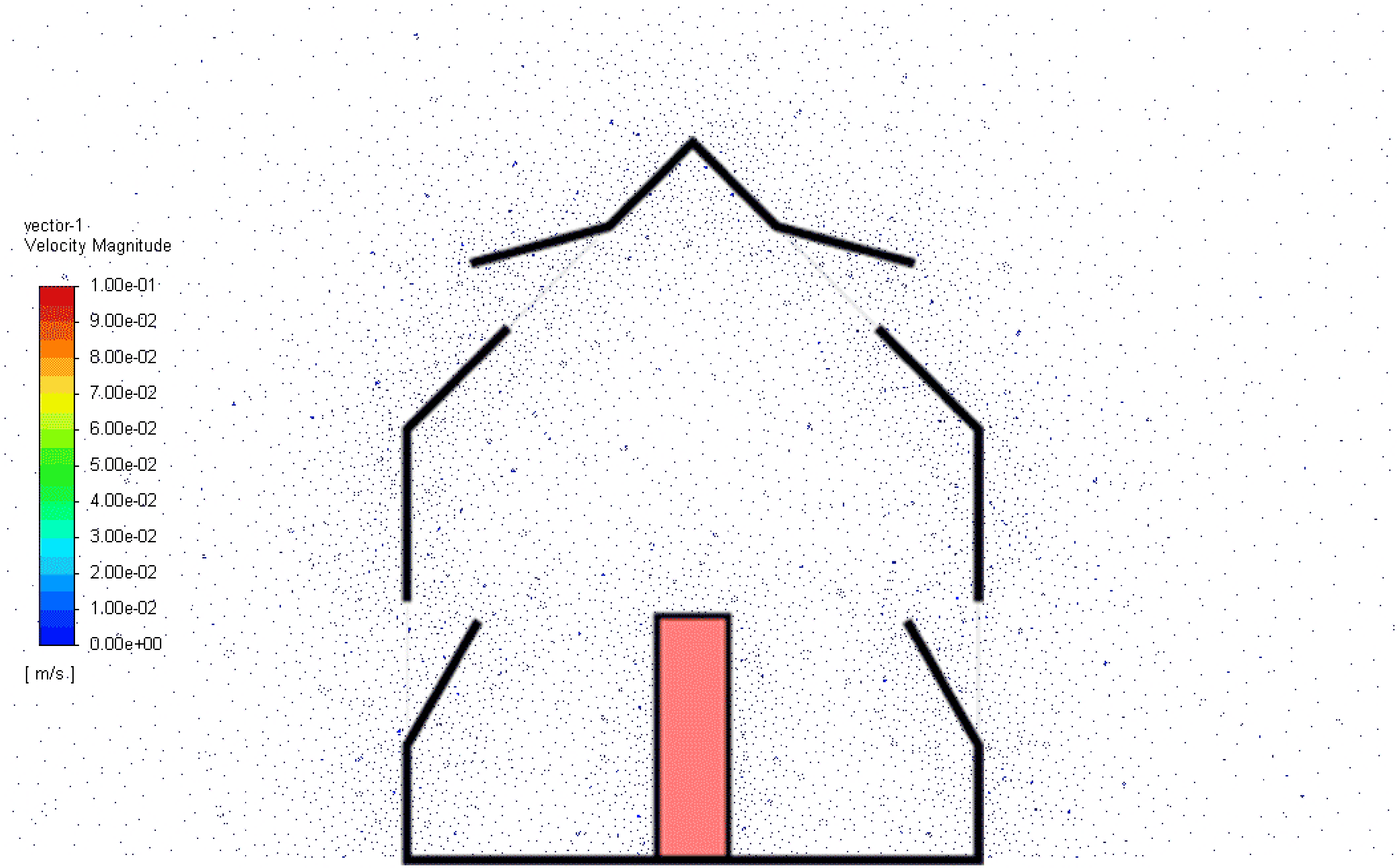


Temperature



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 ~ 10^-2), further improvement could be tested:

a. Reduce dt and dx;
b. Optimize mesh (e.g. inflation layers at walls)