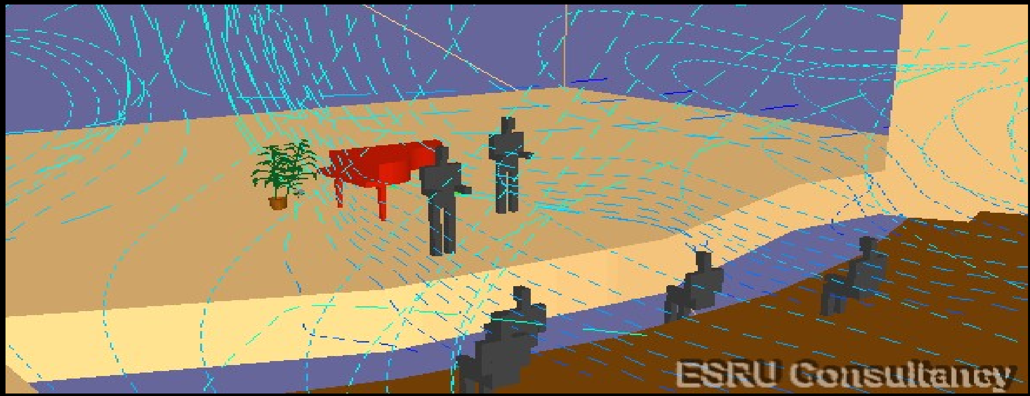
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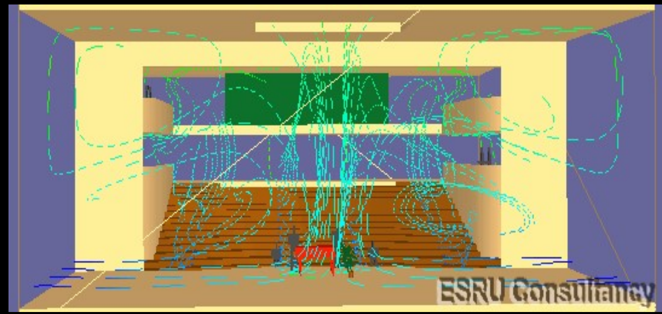
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Fluid flow


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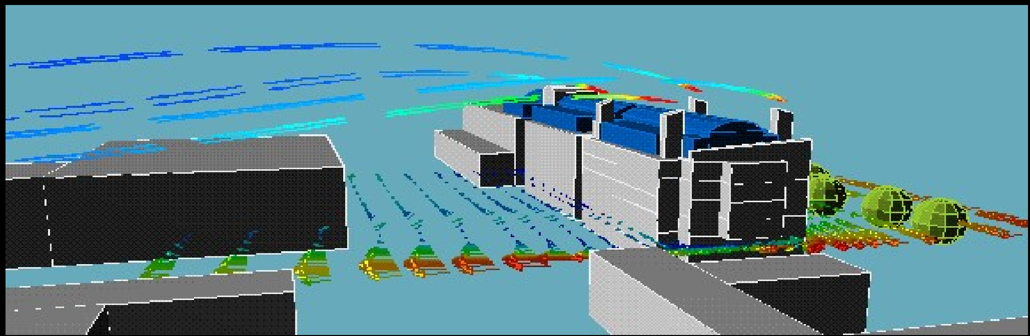

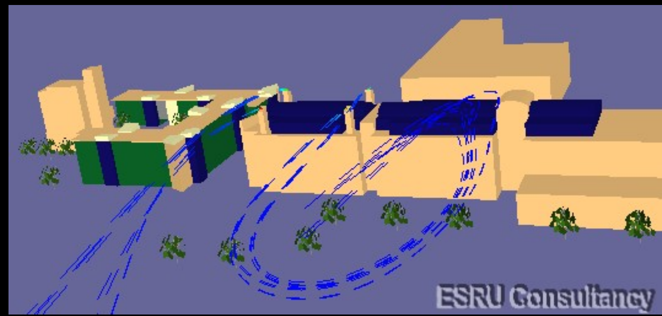
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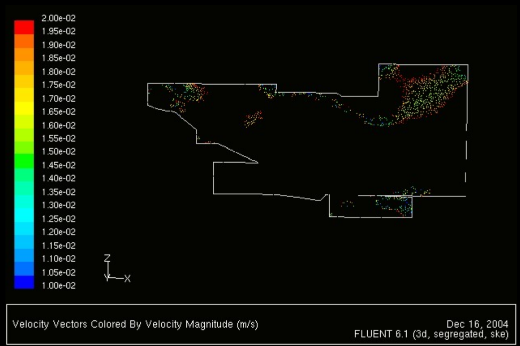
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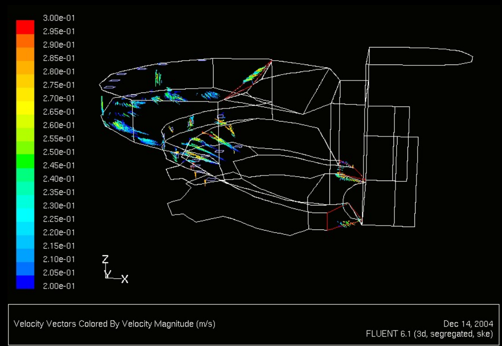
Dec 16, 2004
FLUENT 6.1 (3d, segregated, ske)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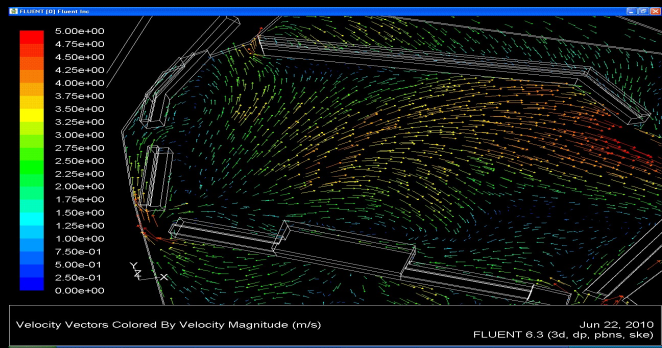
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Velocity Vectors Colored By Velocity Magnitude (m/s)
Jun 22, 2010
FLUENT 6.3 (3d, dp, pbns, ske)

Calculating equation coefficients

Construction Conservation Equation

$$\left(2\rho_I(t+\delta t)C_I(t+\delta t)+\frac{2\delta t\,k(t+\delta t)}{\delta x_I^2}\right)\theta(I,t+\delta t) - \frac{\delta t\,k(t+\delta t)}{\delta x_I^2}\theta(I-1,t+\delta t) - \frac{\delta t\,k(t+\delta t)}{\delta x_I^2}\theta(I+1,t+\delta t) - \frac{\delta t\,q_I(t+\delta t)}{\delta x_I \delta x_J \delta x_K}$$
$$= \left(2\rho_I(t)C_I(t)-\frac{2\delta t\,k(t)}{\delta x_I^2}\right)\theta(I,t) + \frac{\delta t\,k(t)}{\delta x_I^2}\theta(I-1,t) + \frac{\delta t\,k(t)}{\delta x_I^2}\theta(I+1,t) + \frac{\delta t\,q_I(t)}{\delta x_I \delta x_J \delta x_K}.$$

Surface Conservation Equation

$$\left(2W_I(t+\delta t)+\frac{\delta t\,k'_{I-1,I}(t+\delta t)}{\delta x_{I-1,I}\delta_{I,I-1}}+\frac{\delta t\,h_{cI+1,I}(t+\delta t)}{\delta_{I,I-1}}+\frac{\delta t\sum_{s=1}^{N}h_{rs,I}(t+\delta t)}{\delta_{I,I-1}}\right)\theta(I,t+\delta t)$$
$$-\frac{\delta t\,k'_{I-1,I}(t+\delta t)}{\delta x_{I-1,I}\delta_{I,I-1}}\theta(I-1,t+\delta t)-\frac{\delta t\,h_{cI+1,I}(t+\delta t)}{\delta_{I,I-1}}\theta(I+1,t+\delta t)$$
$$-\frac{\delta t\sum_{s=1}^{N}h_{rs,I}(t+\delta t)\theta(s,t+\delta t)}{\delta_{I,I-1}}-\frac{\delta t\,q_{PI}(t+\delta t)}{\delta_{I,I-1}\delta_{J-1,J+1}\delta_{K-1,K+1}}$$
$$=\left(2W_I(t)-\frac{\delta t\,k'_{I-1,I}(t)}{\delta x_{I-1,I}\delta_{I,I-1}}-\frac{\delta t\,h_{cI+1,I}(t)}{\delta_{I,I-1}}-\frac{\delta t\sum_{s=1}^{N}h_{rs,I}(t)}{\delta_{I,I-1}}\right)\theta(I,t)$$
$$+\frac{\delta t\,k'_{I-1,I}(t)}{\delta x_{I-1,I}\delta_{I,I-1}}\theta(I-1,t)+\frac{\delta t\,h_{cI+1,I}(t)}{\delta_{I,I-1}}\theta(I+1,t)+\frac{\delta t\sum_{s=1}^{N}h_{rs,I}(t)\theta(s,t)}{\delta_{I,I-1}}$$
$$+\frac{\delta t[q_{PI}(t)+q_{SI}(t)+q_{RI}(t)+q_{SI}(t+\delta t)+q_{RI}(t+\delta t)]}{\delta_{I,I-1}\delta_{J-1,J+1}\delta_{K-1,K+1}}+\varepsilon.$$

Fluid Conservation Equation

$$\left(2W_I(t+\delta t)+\frac{\delta t\sum_{i=1}^{N}h_{ci,I}(t+\delta t)\delta A_{i,I}}{\delta V_I}+\frac{\delta t\sum_{j=1}^{M}v_{j,I}(t+\delta t)\bar{\rho}_{j,I}(t+\delta t)\bar{C}_{j,I}(t+\delta t)}{\delta V_I}\right)\theta(I,t+\delta t)$$
$$-\frac{\delta t\sum_{i=1}^{N}h_{ci,I}(t+\delta t)\delta A_{i,I}\theta(i,t+\delta t)}{\delta V_I}-\frac{\delta t\sum_{j=1}^{M}v_{j,I}(t+\delta t)\bar{\rho}_{j,I}(t+\delta t)\bar{C}_{j,I}(t+\delta t)\theta(j,t+\delta t)}{\delta V_I}$$
$$-\frac{\delta t\,q_I(t+\delta t)}{\delta V_I}=\left(2W_I(t)-\frac{\delta t\sum_{i=1}^{N}h_{ci,I}(t)\delta A_{i,I}}{\delta V_I}-\frac{\delta t\sum_{j=1}^{M}v_{j,I}(t)\bar{\rho}_{j,I}(t)\bar{C}_{j,I}(t)}{\delta V_I}\right)\theta(I,t)$$
$$+\frac{\delta t\sum_{i=1}^{N}h_{ci,I}(t)\delta A_{i,I}\theta(i,t)}{\delta V_I}+\frac{\delta t\sum_{j=1}^{M}v_{j,I}(t)\bar{\rho}_{j,I}(t)\bar{C}_{j,I}(t)\theta(j,t)}{\delta V_I}+\frac{\delta t\,q_I(t)}{\delta V_I}+\varepsilon$$

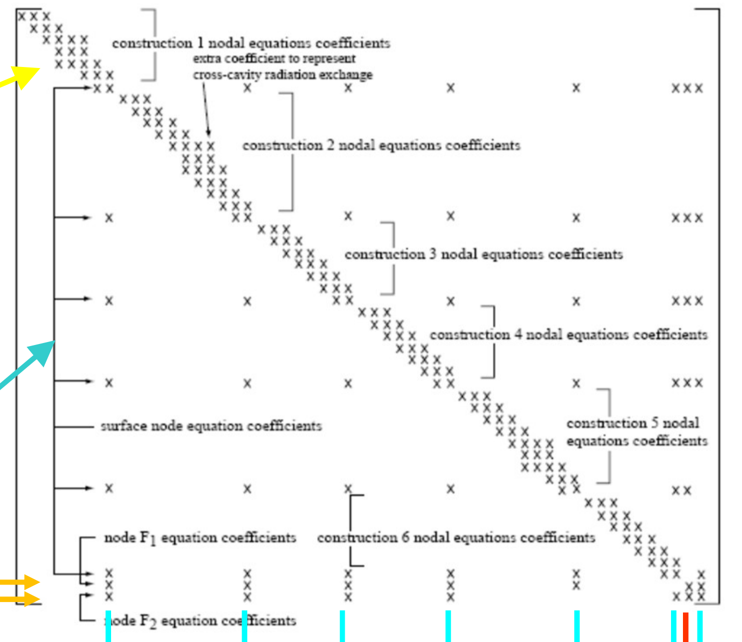
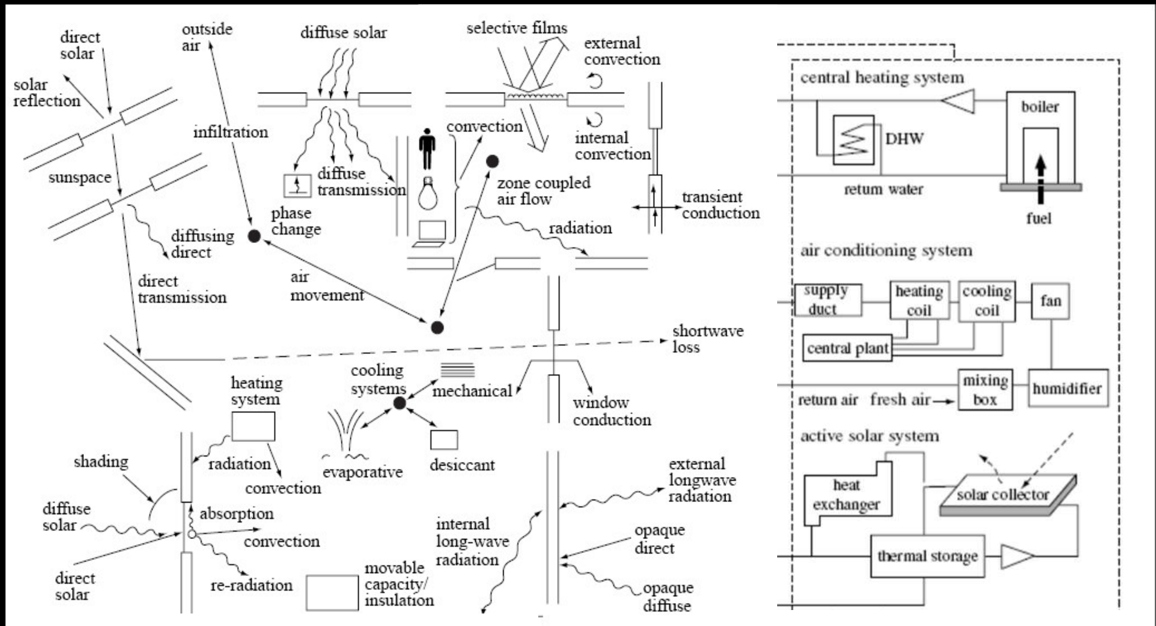


Figure 3.13: The future time-row coefficients matrix (**A**) of the single zone matrix equation $\mathbf{A}\theta_{n+1} = \mathbf{B}\theta_n + \mathbf{C}$.

needs flow estimation

needs radiation and convection estimation

Flow domains



Building flow-paths
Plant components

Two modelling approaches of progressive detail:

- ❑ nodal network - applicable to building infiltration & natural ventilation and plant fluid flows; and
- ❑ computational fluid dynamics - generally applicable.

- ❑ Air/vapour flow through cracks and openings in the building envelope allowing infiltration and natural ventilation.
- ❑ Air/vapour flow through the leakage paths connecting internal spaces and the distribution networks that exist to service the building’s heating, cooling and ventilation demands.
- ❑ Air/vapour/pollutants flow within the interior spaces of the building or the movement of working fluids within HVAC plant components.
- ❑ Water movement (in the liquid and vapour states) within the porous materials comprising the building structure and contents.

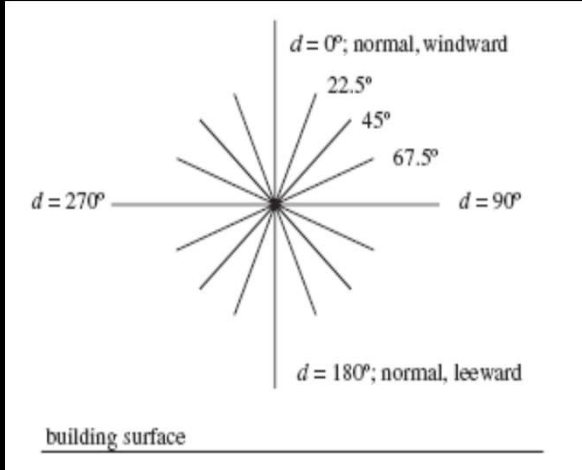
Nodal network method – boundary conditions

- Building surface pressure distribution is wind induced:

$$C_{id} = \frac{P_{id}}{\frac{1}{2}\rho v_r^2}$$

Table 5.1: Pressure coefficient sets.

Pressure coefficients at 22.5° intervals	*Context*
0.70/0.53/0.35/-0.08/-0.50/-0.45/-0.40/-0.30/-0.20/-0.30/-0.40/-0.45/-0.50/-0.08/0.35/0.53	1:1 exposed wall
0.20/0.13/0.05/-0.10/-0.25/-0.23/-0.30/-0.28/-0.25/-0.28/-0.30/-0.28/-0.25/-0.10/0.05/0.13	1:1 sheltered wall
0.50/0.38/0.25/-0.13/-0.50/-0.65/-0.80/-0.75/-0.70/-0.75/-0.80/-0.65/-0.50/-0.13/0.25/0.38	2:1 exposed long wall
0.06/-0.03/-0.12/-0.16/-0.20/-0.29/-0.38/-0.34/-0.30/-0.34/-0.38/-0.29/-0.20/-0.16/-0.12/-0.03	2:1 sheltered long wall
0.60/0.40/0.20/-0.35/-0.90/-0.75/-0.60/-0.48/-0.35/-0.48/-0.60/-0.75/-0.90/-0.35/0.20/0.40	1:2 exposed short wall
0.18/0.17/0.15/-0.08/-0.30/-0.31/-0.32/-0.26/-0.20/-0.26/-0.32/-0.31/-0.30/-0.08/0.15/0.16	2:1 sheltered short wall
-0.80/-0.75/-0.70/-0.65/-0.60/-0.55/-0.50/-0.45/-0.40/-0.45/-0.50/-0.55/-0.60/-0.65/-0.70/-0.75	1:1 exposed roof <10°
-0.40/-0.45/-0.50/-0.55/-0.60/-0.55/-0.50/-0.45/-0.40/-0.45/-0.50/-0.55/-0.60/-0.55/-0.50/-0.45	1:1 exposed roof 10-30°
0.30/-0.05/-0.40/-0.50/-0.60/-0.50/-0.40/-0.45/-0.50/-0.45/-0.40/-0.50/-0.60/-0.50/-0.40/-0.05	1:1 exposed roof >30°
-0.70/-0.70/-0.70/-0.75/-0.80/-0.75/-0.70/-0.70/-0.70/-0.70/-0.70/-0.75/-0.80/-0.75/-0.70/-0.70	2:1 exposed roof <10°
-0.70/-0.70/-0.70/-0.70/-0.70/-0.65/-0.60/-0.55/-0.50/-0.55/-0.60/-0.65/-0.70/-0.70/-0.70/-0.70	2:1 exposed roof 10-30°
0.25/0.13/0.00/-0.30/-0.60/-0.75/-0.90/-0.85/-0.80/-0.85/-0.90/-0.75/-0.60/-0.30/0.00/0.13	2:1 exposed roof >30°

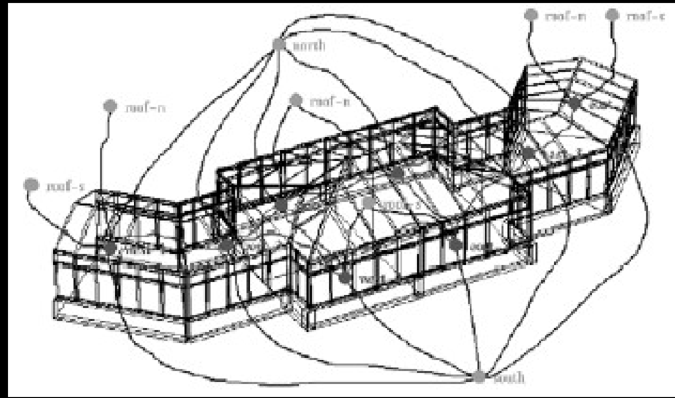


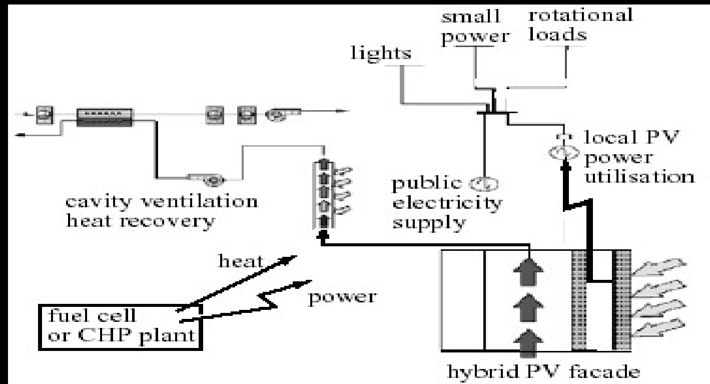
- Where the reference wind speed, v_r, is a local wind speed, the free stream wind speed is modified as a function of any height difference and the effect of local terrain roughness using an assumed vertical wind profile (see notes).

Nodal network method – system discretisation

- Nodes represent discrete, homogeneous fluid volumes characterised by:
  - temperature;
  - static pressure;
  - height relative to an arbitrary datum.

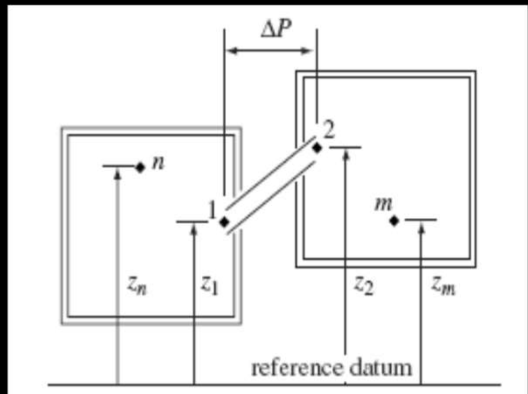
Internal, unknown condition	height (m)
Internal, known condition	height (m), total pressure (Pa) and temperature (°C)
Boundary, known pressure	height (m), total pressure (Pa) and temperature (°C)
Boundary, wind pressure	height (m), pressure coefficient set, surface azimuth (° from N)





- Buoyancy effects:
  - pressure drop across a component determined from Bernoulli's equation (one-dimensional steady flow of an incompressible fluid):

$$\Delta P = (p_1 + \rho V_1^2/2) - (p_2 + \rho V_2^2/2) + \rho_i g(z_1 - z_2)\ ;\ i = n, m$$



Nodal network method – component models

- Component models derived from experiments, for example the mass flow rate through:
  - a restriction with a large aspect ratio (such as a crack)

$$\dot{m} = ka(\Delta P)^{x}$$

$$x = 0.5 + 0.5\exp(-W/2)$$

$$k = 9.7(0.0092)^{x}$$

  - through an open window

$$q = C_d A\sqrt{\frac{2\Delta P}{\rho_i}}$$

  - through a large vertical opening (such as a doorway)

$$v = (2/3)[C_D W h (2/\rho)^{\frac{1}{2}}(C_a^{\frac{1}{2}} - C_b^{\frac{1}{2}})/C_t]$$

Component	*Model*
Power law volume flow resistance	$\dot{m} = \rho a \Delta P^{n}$
Power law mass flow resistance	$\dot{m} = a\Delta P^{b}$
Power law mass flow resistance	$\dot{m} = a\sqrt{\rho}\Delta P^{b}$
Quadratic law volume flow resistance	$\Delta P = a\dot{m}/\rho + b(\dot{m}/\rho)^2$
Quadratic law mass flow resistance	$\Delta P = a\dot{m} + b\dot{m}^2$
Constant volume flow rate component	$\dot{m} = \rho r_v$
Constant mass flow rate component	$\dot{m} = r_m$
Common orifice flow component	$\dot{m} = C_d A\sqrt{2\rho\Delta P}$
Laminar pipe flow component	$\dot{m} = \frac{\rho\Delta P\pi R^4}{8\mu L_p}$
Specific air flow opening	$\dot{m} = 0.65A\sqrt{2\rho\Delta P}$
Specific air flow crack	$\dot{m} = f(\rho, k, \Delta P)$ (see text)
Specific air flow door	$\dot{m} = f(W_d, H, H_r, C_d, \Delta P)$ (see text)
General flow conduit (duct or pipe)	$\dot{m} = A_c\sqrt{\frac{2\rho\Delta P}{f\,L_{p/D_h} + \sum C_i}}$; $f = 1/2\log(5.74/Re^{0.901} + 0.27k_r/D_h)^2$
General flow inducer (pump or fan)	$\Delta P = \sum_{i=0}^{3} a_i(\dot{m}/\rho)^i$; $\dot{q}_{min} \le \dot{m}/\rho \le \dot{q}_{max}$
General flow corrector	$\dot{m} = \rho\, k_v\left[\frac{\Delta P\rho_0}{\Delta P_0\rho}\right]$
Flow corrector with polynomial local loss	$\dot{m} = A_c\left[\frac{2\rho\Delta P}{C}\right]^{\frac{1}{2}}$; $C = \sum_{i=0}^{3} a_i(H/H_{100})^i$
Ideal (frictionless) open/shut flow controller	$\dot{m} = 0$ or $\dot{m} = \rho\,\dot{q}$

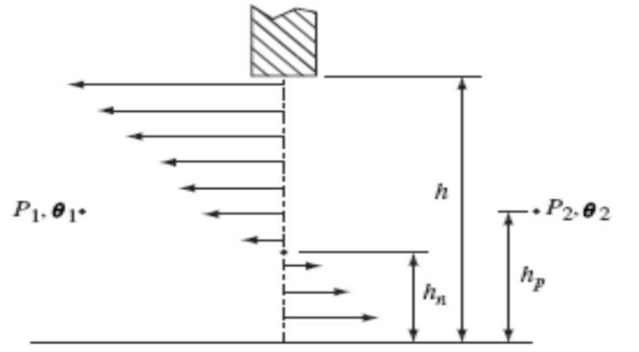


Figure 5.4: Bi-directional air flow across a doorway.

Nodal network method – iterative solution procedure

- ❑ Nodal mass flow rate residual (error) for a current iteration: $R_i = \sum_{k=1}^{K_i} \dot{m}_k$
- ❑ Required nodal pressure corrections: $P^* = P - C$
- ❑ Pressure correction vector: $C = J^{-1} R$
- ❑ Jacobian matrix: $J_{n,n} = \sum_{i=1}^{L} \left(\frac{\partial \dot{m}}{\partial \Delta P} \right)_i$ $J_{n,m} = \sum_{i=1}^{M} - \left(\frac{\partial \dot{m}}{\partial \Delta P} \right)_i \quad ; n \neq m$
- ❑ Solver uses Crout's method with partial pivoting:
  - $J\,C = (L\,U)\,C = L\,(U\,C) = R$
  - **J** decomposed into a lower triangular matrix, **L**, and an upper triangular matrix, **U**, such that **L U** = **J**;
  - solve, by forward substitution, for the vector **Y** such that **L Y** = **R** and then solve (by back substitution) **U C** = **Y;**
  - advantage is that both substitutions are trivial;
  - $P_i = P_i^* - C_i/(1 - r)$
- ❑ Convergence criterion: $\sum \dot{m}_k \rightarrow 0$

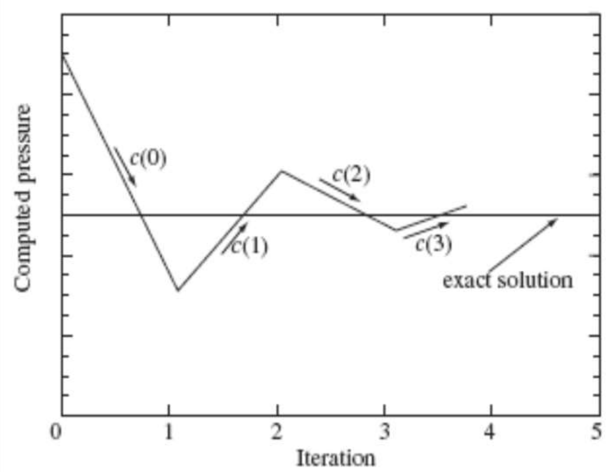
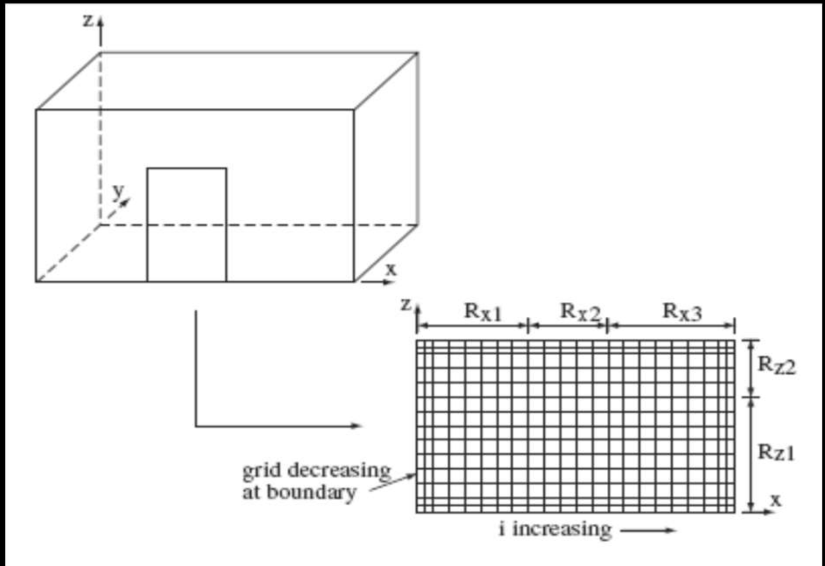


Figure 5.5: Example of successive computed values of pressure and oscillating pressure correction at a single node.

See tutorial
questions 7 & 8
and learn method

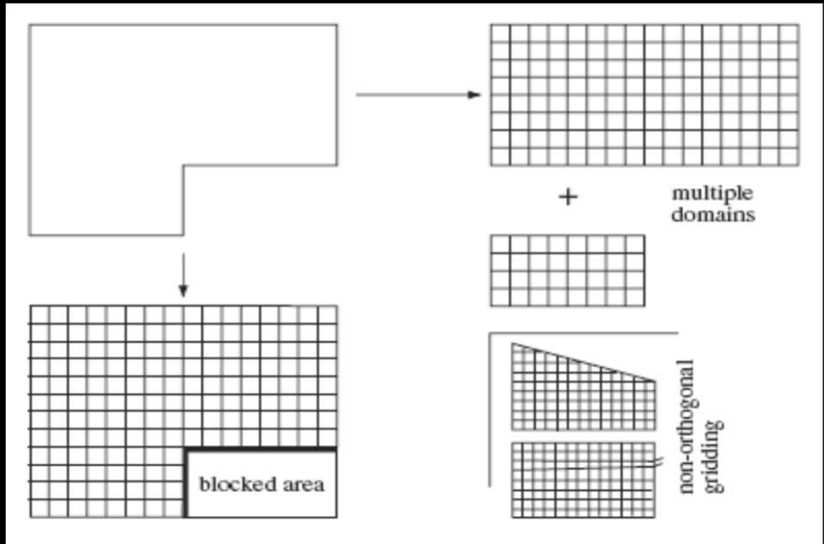
Computational Fluid Dynamics – domain discretisation

Energy system geometries are typically orthogonal …



CFD domain discretisation.

simple devices used for non-orthogonal cases …



Treatment of complex geometries.

Computational Fluid Dynamics – conservation equations

- The Boussinesq approximation is usually applied:
  - air density held constant;
  - effects of buoyancy included within the momentum equation.

- Energy, mass and momentum equations applied:

$$\frac{\partial}{\partial t}(\rho\phi) = \frac{\partial}{\partial x_i}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_i} - \rho U_i \phi\right) + S_\phi$$

The rate of increase of φ within a fluid element = the rate of increase of φ due to diffusion - the net rate of flow of φ out of the element + the rate of increase of φ due to sources.

Table 5.7: Transport variables (ϕ), diffusion coefficients (Γ_ϕ) and source terms (S_ϕ).

Equation Type	ϕ	Γ_ϕ	S_ϕ
Continuity	1	-	-
Momentum	u_i	μ_{ef}	$-\frac{\partial p}{\partial x_i} - \rho g \beta(\theta_\infty - \theta)$
Energy	H	Γ_T	S_H
Species	C	Γ_C	S_C
Turbulent kinetic energy	k	$\frac{\mu_{ef}}{\sigma_k}$	$G - C_D\rho\varepsilon - G_b$
Dissipation rate of k	ε	$\frac{\mu_{ef}}{\sigma_\varepsilon}$	$C_1\frac{\varepsilon}{k}G - C_2\rho\frac{\varepsilon^2}{k} - C_3\frac{\varepsilon}{k}G_b$

$$\Gamma_T = \frac{\mu}{Pr} + \frac{\mu_t}{\sigma_T} \;;\; \Gamma_C = \frac{\mu}{Sc} + \frac{\mu_t}{\sigma_C} \;;\; \mu_{ef} = \mu_t + \mu \;;\; \rho = \rho(T, C)$$

$$G_b = g\left(\beta_T \frac{\mu_t}{\sigma_T}\frac{\partial T}{\partial x_i} + \beta_C \frac{\mu_t}{\sigma_C}\frac{\partial C}{\partial x_i}\right) \;;\; G = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$$

$$C_D = 1.0 \;;\; C_1 = 1.44 \;;\; C_2 = 1.92 \;;\; \sigma_k = 1.0 \;;\; \sigma_\varepsilon = 1.3 \;;\; \sigma_T = 0.9 \;;\; \sigma_C = 0.9$$

where μ is molecular viscosity (kg $m^{-1}s^{-1}$), μ_t is eddy viscosity, P is pressure (N m^{-2}), g the gravitational acceleration (m s^{-2}), C_p the specific heat (J $kg^{-1}K^{-1}$), q''' is heat generation (W m^{-3}), Pr is the Prandtl Number, Sc is the Schmidt Number, σ_k is the turbulent energy diffusion coefficient, σ_ε is the turbulent energy dissipation diffusion coefficient, σ_T is the turbulent Prandtl Number, σ_C is the turbulent Schmidt Number, β_T is the thermal expansion coefficient (1/K).

- To avoid direct modelling turbulent flows, a turbulence transport model is used whereby the influence of turbulence on the time-averaged motion of air may be determined, e.g. the standard k-ε model used to determine the eddy viscosity, μ_t, at each grid point as a function of the local turbulent kinetic energy (k) and its rate of dissipation (ε):

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

- Conservation equations discretised by the finite volume method to obtain a set of linear equations of the form:

$$a_p \phi_p = \sum_i a_i \phi_i + b$$

$$C_s(t+\delta t)\theta(I, t+\delta t) - \sum_{i=1}^{N} C_{ci}(t+\delta t)\theta(i, t+\delta t) - \frac{\delta t\, q_I(t+\delta t)}{\delta V_I} = C_s(t)\theta(I, t) + \sum_{i=1}^{N} C_{ci}(t)\theta(i, t) + \frac{\delta t\, q_I(t)}{\delta V_I} + \varepsilon$$

Computational Fluid Dynamics – initial and boundary conditions

- Initial values of ρ, u_i and θ are required at time $t = 0$ for all domain cells.

- For solid surfaces, the required boundary conditions include the temperature (or flux) at points adjacent to the domain cells.

- For cells subjected to an in-flow from ventilation openings and doors/windows, the mass/momentum/energy/species exchange must be given in terms of the distribution of relevant variables of state: U, V, W, H, k, ε and C.

- At outlets, the normal practice is to impose a constant pressure and the conditions $\partial u_n/\partial n = 0$, $\partial \theta/\partial n = 0$, $\partial k/\partial n = 0$, $\partial \varepsilon/\partial n = 0$, where n indicates the direction normal to the boundary.

- Where the CFD model is conflated with the building and network flow models, these boundary conditions will be time dependent.

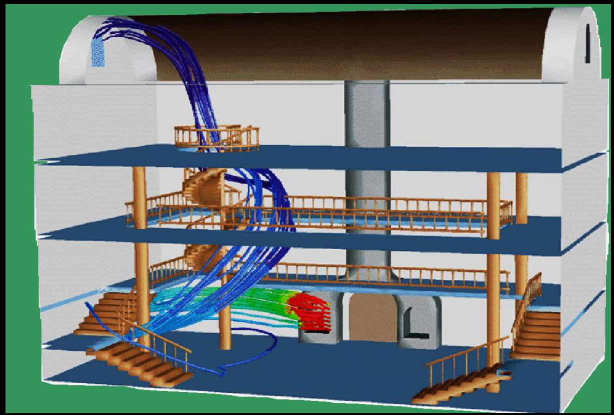
- Where a method exists to consider the applicability of different near-wall turbulence models, then parameters such as surface convection coefficients may additionally be assigned as boundary conditions.

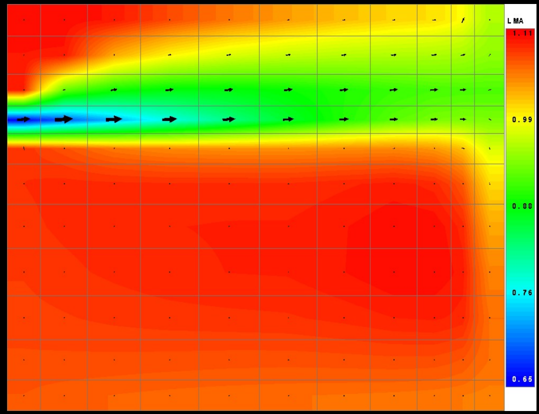
Computational Fluid Dynamics – iterative solution procedure

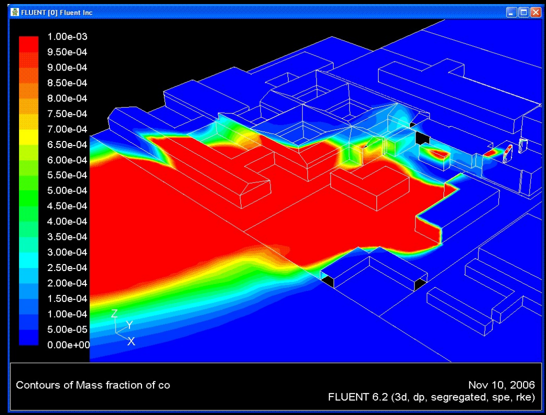
- SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) method:
  - pressure of cells linked to the velocities connecting with surrounding cells in a manner that conserves continuity;
  - accounts for the absence of an equation for pressure by establishing a modified form of the continuity equation to represent the pressure correction that would be required to ensure that the velocity components determined from the momentum equations move the solution towards continuity;
  - uses a guessed pressure field to solve the momentum equations for intermediate velocity components U, V and W – these are then used to estimate the required pressure field correction from the modified continuity equation;
  - the energy equation, and any other scalar equations (e.g. for concentration), are then solved and the process iterates until convergence is attained;
  - to avoid numerical divergence, under relaxation is applied to the pressure corrections.

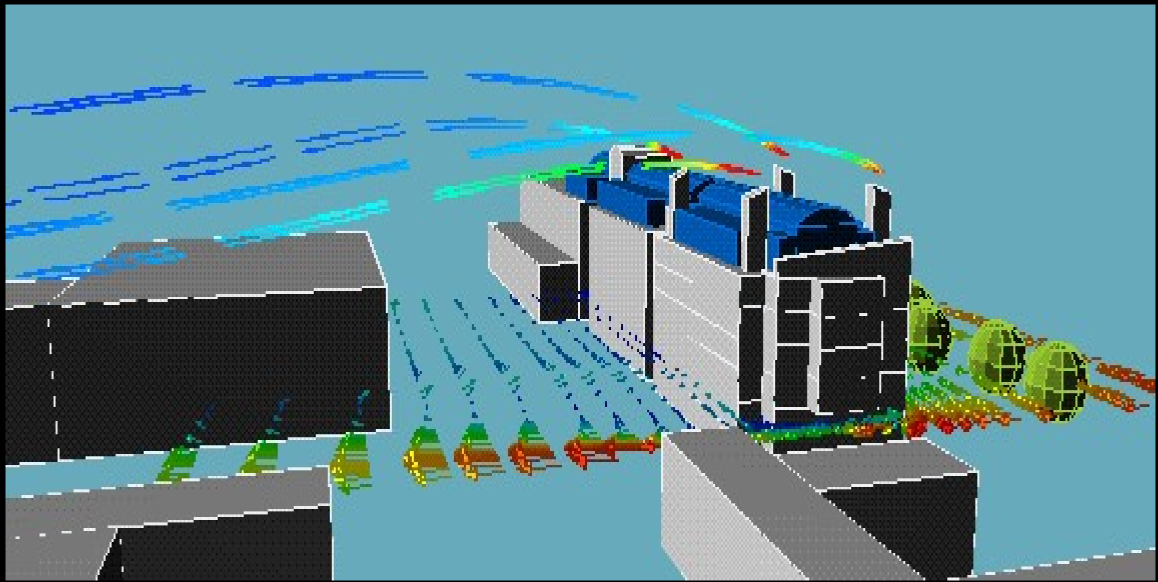
- Variants of the SIMPLE method have been developed in order to reduce the computational burden and assist convergence:
  - SIMPLE-R(evised) - the pressure field is obtained directly (i.e. without the need for correction) from a pressure equation derived from the continuity equation;
  - SIMPLE-C(onsistent) - the simplifications applied to the momentum/continuity equations to obtain the pressure field correction are less onerous;

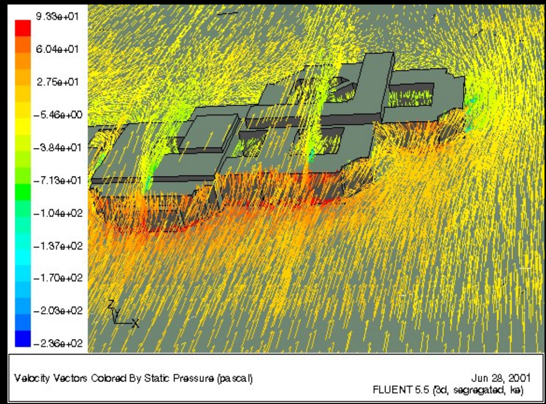
Computational Fluid Dynamics – results





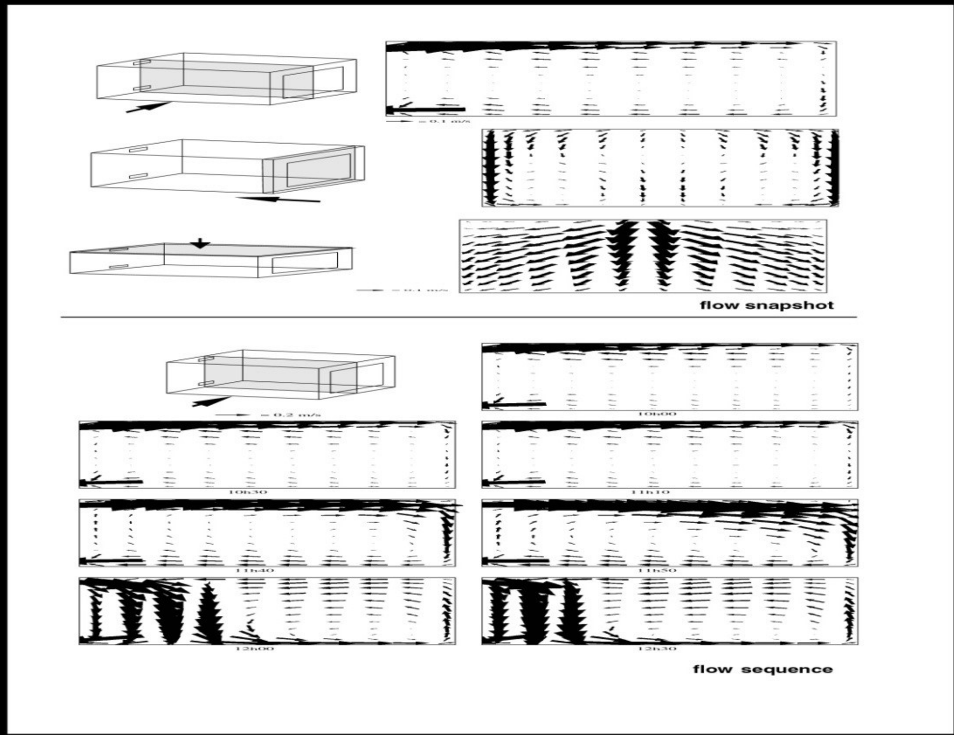


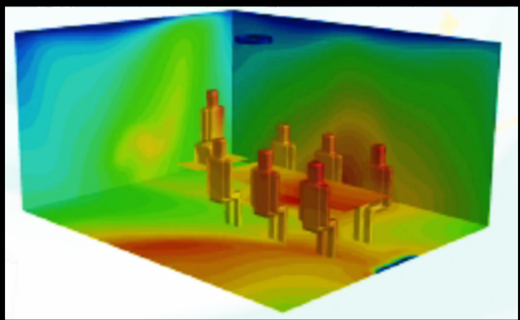




Computational Fluid Dynamics – building/plant conflation

- The conflation of CFD and building/plant simulation gives relevant indicators:
  - variation in vertical air temperature between floor and head height;
  - absolute temperature of the floor;
  - radiant temperature asymmetry;
  - unsatisfactory ventilation rate;
  - unsatisfactory CO_2 level;
  - local draught assessed on the basis of the turbulence intensity distribution;
  - additional air speed required to off-set an elevated temperature;
  - comfort check based on effective temperature;
  - mean age of air.





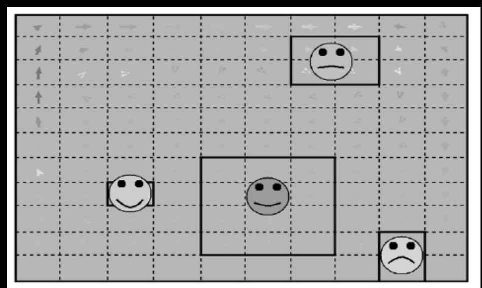
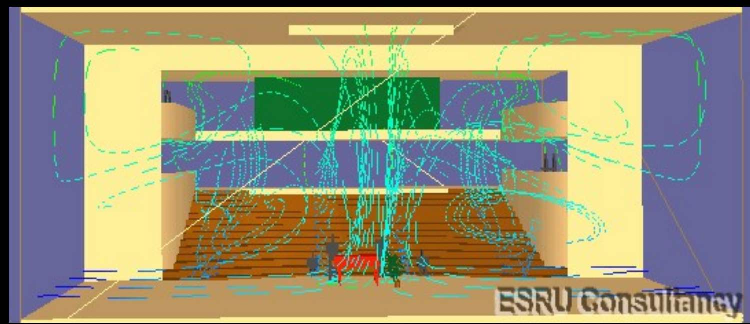
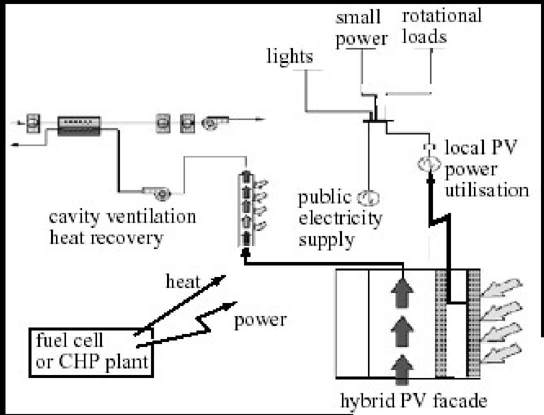
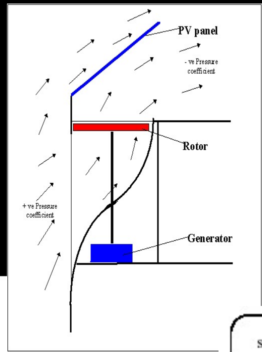


Figure 5.9: Integrated modelling supports the assessment of variations in air quality and thermal comfort.



Linking the building, plant and flow domains





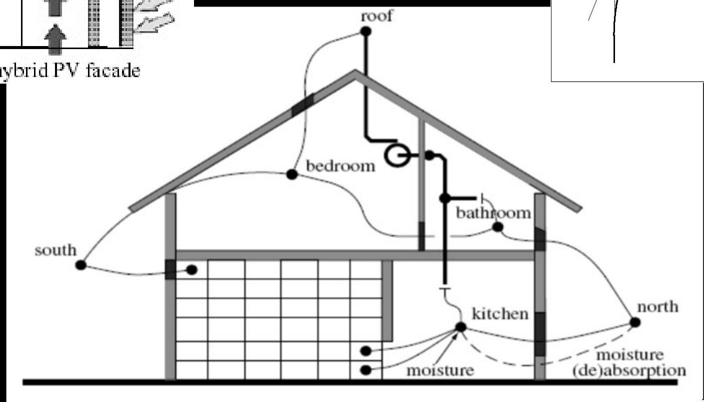
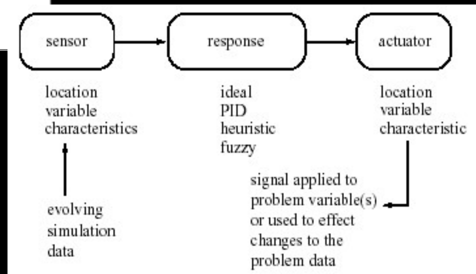


Figure 5.11: Coupling plant and flow models.



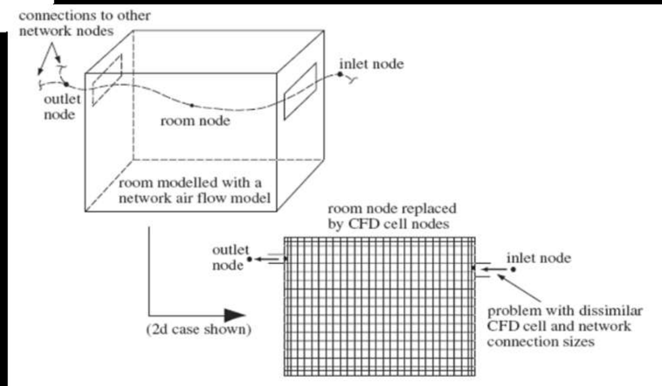


Figure 5.10: Coupling network flow and CFD models.

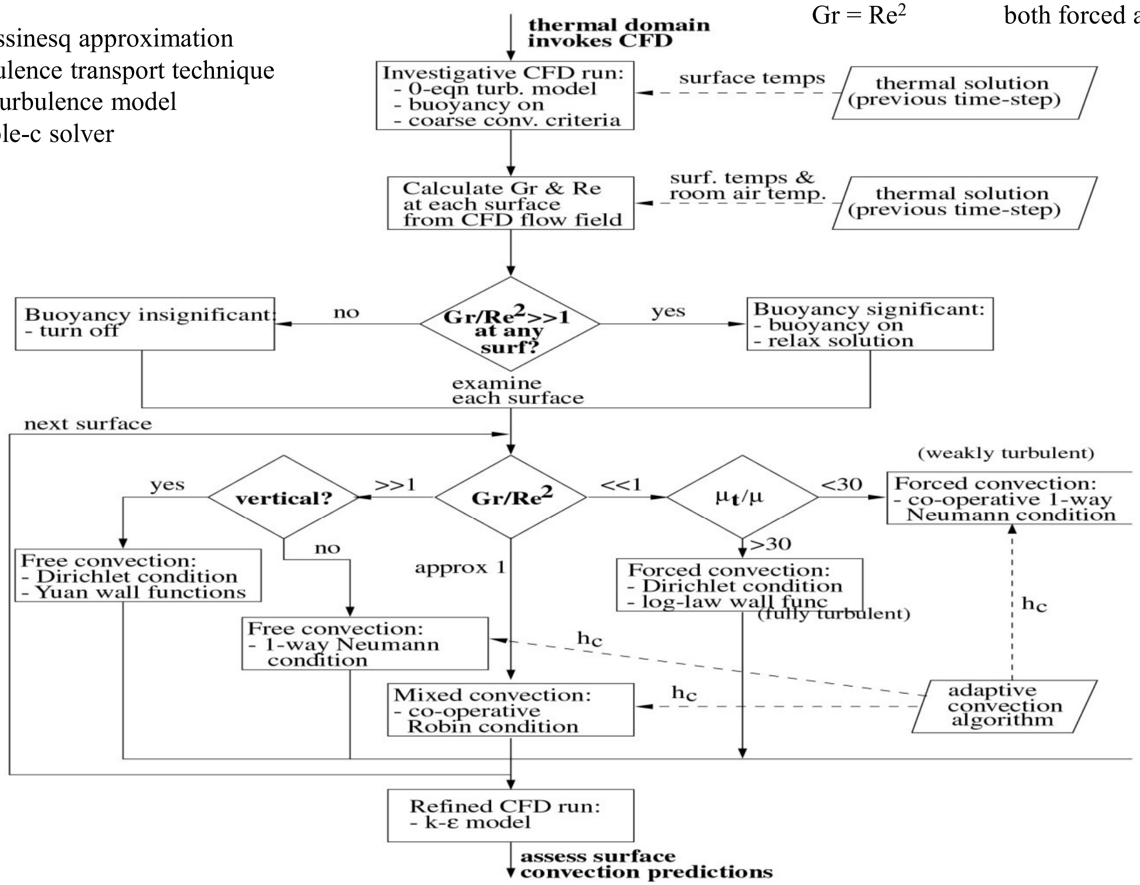
Linking the building, plant and flow domains – turbulence

Gr – how buoyant
Re – how forced

$Gr/Re^2 << 1$	forced convection effects overwhelm free convection
$Gr/Re^2 >> 1$	free convection effects dominate
$Gr = Re^2$	both forced and free convection effects significant

μ_t – eddy viscosity
μ – molecular viscosity
$\mu_t/\mu < 30$ flow is weakly turbulent

- ❑ Boussinesq approximation
- ❑ turbulence transport technique
- ❑ k-ε turbulence model
- ❑ simple-c solver



Dirichlet BC: fixed surface temp. $\theta = \theta_S$

Neumann BC: fixed surface heat flux $k\frac{\delta\theta}{\delta n} = q$

Robin BC: heat flux proportional to local heat transfer $k\frac{\delta\theta}{\delta n} = h_c(\theta - \theta_S)$

dynamic CFD model configuration

Linking the building, plant and flow domains – hand-shaking

turbulence model	hand-shaking mechanism	CFD thermal boundary condition	applicability
$k-\varepsilon$ model and log-law wall functions (for momentum eqs)	one-way	+Dirichlet +CFD calculates q_{conv} with log-law wall function	+predicting flow &temp. field +not suitable for buoyancy-driven ow +not suitable for o ws strongly affected by q_{conv}
		+Neumann +thermal domain $\rightarrow T_{surf}$ +thermal domain $\rightarrow T_{room-air}$ +ACA $\rightarrow h_c$	+predicting flow and temp. field +suitable for flows strongly affected by q_{conv}
		+co-op Neumann +thermal domain $\rightarrow T_{surf}$ +CFD $\rightarrow T_{room-air}(avg)$ +ACA $\rightarrow h_c$	+predicting flow and temp.field +suitable for flows strongly affected by q_{conv} +useful when room stratfied
		+co-op Robin +thermal domain $\rightarrow T_{surf}$ +CFD $\rightarrow T_p$ (local) + ACA $\rightarrow h_c$	+prediction flow and temp.field +suitable for flows strongly affected by q_{conv} +useful when room stratified
	conditional two-way	+Dirichlet +CFD calculates q_{conv} with log-law wall functions	+predicting flow and temp. field +enhancing surface conv. calcs +not suitable for buoynacy-driven flow +not suitable for flows strongly affected by q_{conv} +next-to-wall points must be properly placed
		+co-op Robin +thermal domain $\rightarrow T_{surf}$ +CFD $\rightarrow T_p$ (local) + ACA $\rightarrow h_c$	+predicting flow and temp. field +enhancing surface conv. calcs +suitable for o ws strongly affected by q_{conv} +useful when room stratified
$k-\varepsilon$ model and Yuan wall functions	one-way	+Dirichlet +CFD calculated q_{conv} with Yuan wall function	+predicting flow and temp. field +only suitable for buoyancy-driven flow +only suitable for vertical surfaces
	conditional two-way	+Dirichlet +CFD calculated q_{conv} with Yuan wall function	+predicting flow and temp. field +enhancing surface conv. calcs +only suitable for buoyancy-driven flow +only suitable for vertical surfaces
Chen & Xu zero equation model	one-way	+Dirichlet +CFD calculates q_{conv}	+predicting flow and temp. field +suitable for quick indication of flow +less suitable for buoyancy-driven flow +less suitable for flows strongly affected by q_{conv}
	conditional two-way	+Dirichlet +CFD calculates q_{conv}	+predicting flow and temp. field +enhancing surface conv. calcs +less suitable for buoyancy-driven flow +less suitable for flows strongly affected by q_{conv} +next-to wall points must be properly placed

turbulence model applicability

Linking the building, plant & flow domains – surface heat transfer

Table 7.17: h_c correlations for buoyancy and mechanically driven flows.

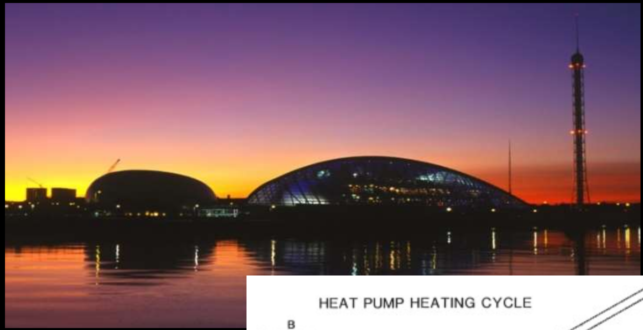
Location	*Applicability*	*h_c correlation*
Correlations from Khalifa and Marshall (1990):		
Wall	• room heated by radiator • radiator not located under window • wall surface adjacent to radiator	$1.98\ \Delta\theta^{0.32}$
Wall	• room heated by radiator • radiator located under window • wall surface adjacent to radiator	$2.30\ \Delta\theta^{0.24}$
	• room with heated walls • not applicable for heated wall	
Wall	• room with circulating fan heater • wall surface opposite fan	$2.92\ \Delta\theta^{0.25}$
Wall	• room with circulating fan heater • wall surface not opposite fan	$2.07\ \Delta\theta^{0.23}$
	• room with heated floor	
	• room heated by radiator • radiator not located under window • wall surface not adjacent to radiator	
Window	• room heated by radiator • radiator located under window	$8.07\ \Delta\theta^{0.11}$
Window	• room heated by radiator • radiator not located under window	$7.61\ \Delta\theta^{0.06}$
Ceiling	• room heated by radiator • radiator located under window	$3.10\ \Delta\theta^{0.17}$
	• room with heated walls	
Ceiling	• room with circulating fan heater	$2.72\ \Delta\theta^{0.13}$
	• room with heated floor	
	• room heated by radiator • radiator not located under window	
Correlations from Awbi and Hatton (1999):		
Wall	• heated	$\frac{1.823\ \Delta^{0.293}}{D_h^{0.121}}$
Floor	• heated	$\frac{2.175\ \Delta^{0.308}}{D_h^{0.076}}$
Correlations from Fisher (1995) and Fisher and Pederson (1997):		
Wall	• ceiling jet in isothermal room#	$-0.199 + 0.190\ (ACR)^{0.8}$
Floor	• ceiling jet in isothermal room#	$0.159 + 0.116\ (ACR)^{0.8}$
Ceiling	• ceiling jet in isothermal room#	$-0.166 + 0.484\ (ACR)^{0.8}$
Wall	• free horizontal jet in isothermal room	$-0.110 + 0.132\ (ACR)^{0.8}$
Floor	• free horizontal jet in isothermal room	$0.704 + 0.168\ (ACR)^{0.8}$
Ceiling	• free horizontal jet in isothermal room	$0.064 + 0.00444\ \frac{(ACR)^{2.8}}{\Delta T}$

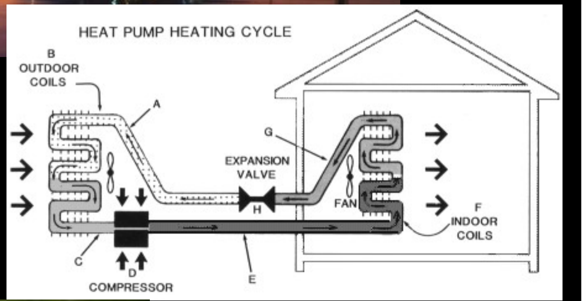
Table 7.18: h_c correlations for the mixed flows (from Beausoleil-Morrison 2000).

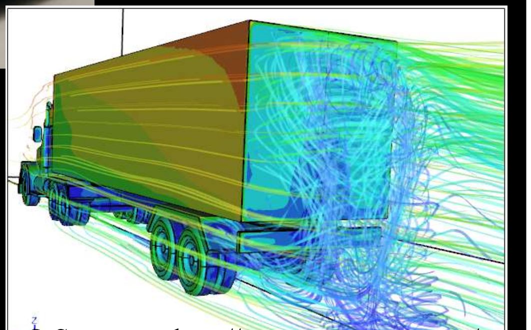
Location	*Applicability*	*h_c correlation*
Correlations from Beausoleil-Morrison (2000)		
Wall	• assisting forces	$\left(\left\{\left[1.5\left(\frac{\lvert\Delta\theta\rvert}{H}\right)^{1/4}\right]^6+\left[1.23\lvert\Delta\theta\rvert^{1/3}\right]^6\right\}^{(3\times 1/6)}+\left\{\left[\frac{\theta_s-\theta_d}{\lvert\Delta\theta\rvert}\right]\left[-0.199+0.190(ACR)^{0.8}\right]\right\}^3\right)^{1/3}$
	• opposing forces	$\max\left(\begin{array}{c}\left[\left\{\left[1.5\left(\frac{\lvert\Delta\theta\rvert}{H}\right)^{1/4}\right]^6+\left[1.23\lvert\Delta\theta\rvert^{1/3}\right]^6\right\}^{(3\times 1/6)}-\left\{\left[\frac{\theta_s-\theta_d}{\lvert\Delta\theta\rvert}\right]\left[-0.199+0.190(ACR)^{0.8}\right]\right\}^3\right]^{1/3}\\ 80\%\text{ of }\left\{\left[1.5\left(\frac{\lvert\Delta\theta\rvert}{H}\right)^{1/4}\right]^6+\left[1.23\lvert\Delta\theta\rvert^{1/3}\right]\right\}^{1/6}\\ 80\%\text{ of }\left\{\left[\frac{\theta_s-\theta_d}{\lvert\Delta\theta\rvert}\right]\left[-0.199+0.190(ACR)^{0.8}\right]\right\}\end{array}\right.$
Floor	• buoyant	$\left(\left\{\left[1.4\left(\frac{\lvert\Delta\theta\rvert}{D_h}\right)^{1/4}\right]^6+\left[1.63\lvert\Delta\theta\rvert^{1/3}\right]^6\right\}^{(3\times 1/6)}+\left\{\left[\frac{\theta_s-\theta_d}{\lvert\Delta\theta\rvert}\right]\left[0.159+0.116(ACR)^{0.8}\right]\right\}^3\right)^{1/3}$
	• stably stratified	$\left(\left[0.6\left(\frac{\lvert\Delta\theta\rvert}{D_h}\right)^{1/5}\right]^3+\left\{\left[\frac{\theta_s-\theta_d}{\lvert\Delta\theta\rvert}\right]\left[0.159+0.116(ACR)^{0.8}\right]\right\}^3\right)^{1/3}$
Ceiling	• buoyant	$\left(\left\{\left[1.4\left(\frac{\lvert\Delta\theta\rvert}{D_h}\right)^{1/4}\right]^6+\left[1.63\lvert\Delta\theta\rvert^{1/3}\right]^6\right\}^{(3\times 1/6)}+\left\{\left[\frac{\theta_s-\theta_d}{\lvert\Delta\theta\rvert}\right]\left[-0.166+0.484(ACR)^{0.8}\right]\right\}^3\right)^{1/3}$
	• stably stratified	$\left(\left\{0.6\left(\frac{\lvert\Delta\theta\rvert}{D_h^2}\right)^{1/5}\right\}^3+\left\{\left[\frac{\theta_s-\theta_d}{\lvert\Delta\theta\rvert}\right]\left[-0.166+0.484(ACR)^{0.8}\right]\right\}^3\right)^{1/3}$

ACR is the room air changes per hour, $\Delta\theta$ the surface-to-air temperature difference, θ_s the surface temperature, θ_d the temperature of the air supplied through the ceiling diffuser, H the surface height and D_h the hydraulic diameter of the surface as before.

Linking the building, plant and flow domains – solver co-ordination







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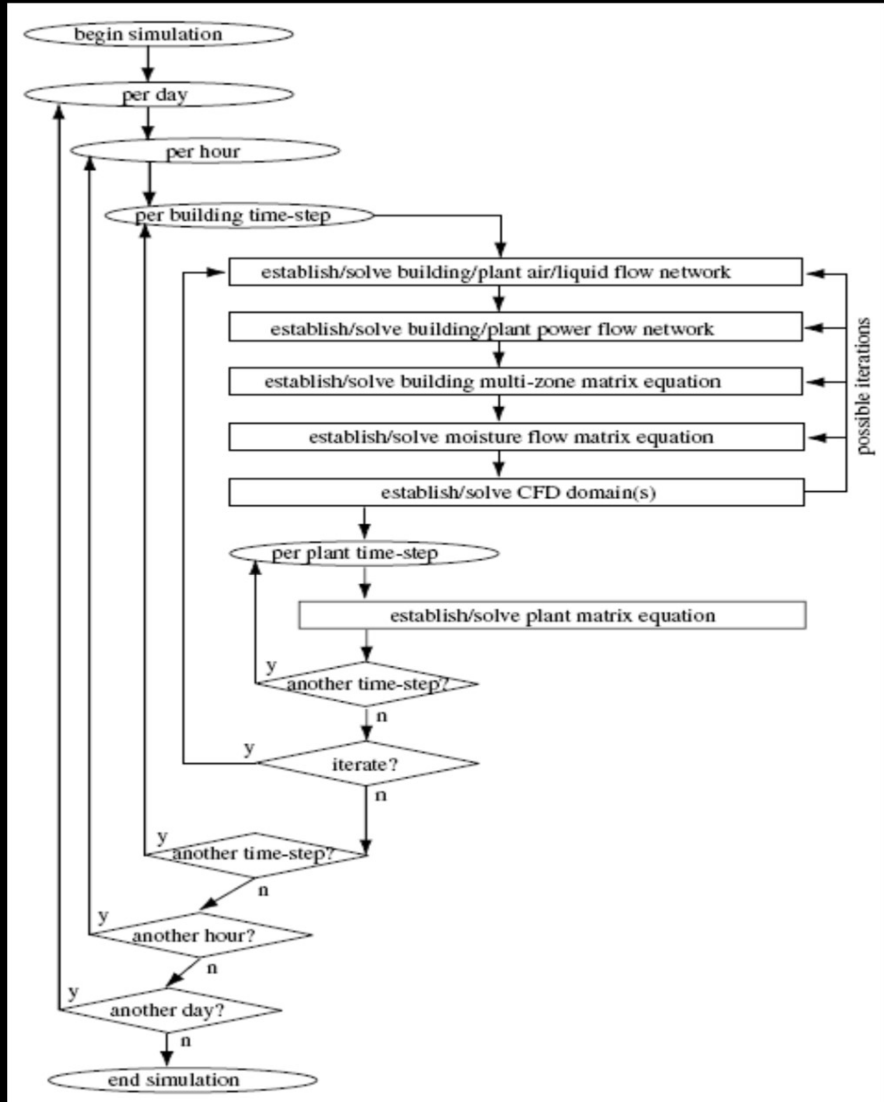

Figure 6.17: Iterative solution of nested domain equations.