Tutorial 8: Fluid flow

Q1. What are the main factors determining air infiltration? In your answer discriminate between factors related to the outdoor environment, the indoor environment, the building and occupants.

Outdoor environment: wind speed, wind direction, surrounding buildings, location type (exposed, urban, city centre *etc.*) and outdoor air temperature.

Indoor environment: indoor air temperature and over/under pressure relative to outside due to mechanical ventilation system.

Building: shape of the building, amount, type and location of envelope openings and leakages, and amount, type and location of inside partition openings and leakages.

Occupants: opening/closing of building openings (doors, windows *etc.*), control of vents and control of mechanical ventilation system(s).

Q2. Describe how the fluid flow within an energy system may be modelled by the nodal network (NN) method.

Boundary conditions are represented by temperature and wind velocity (corrected for terrain roughness), and a pressure coefficient set to account for local obstructions and surface inclination/aspect ratio.

The system is represented as a network of nodes where each node pressure is either internal (unknown) or external (known).

Buoyancy effects are included by modifying the nodal fluid densities as a function of node temperature.

Empirical flow models are introduced to determine the flow within the components that connect nodes as a function of the prevailing pressure difference.

An iterative solution procedure is used to solve the mass balance at each node to yield the node pressures and branch flows.

Q3. Explain the steps involved in solving the equations relating to the flow of fluid within a distributed network using the nodal network method.

1. A guessed value of pressure is assigned to each internal (unknown) node.
2. The mass flow rate between nodes is evaluated by applying the pressure difference to the empirical equations representing connected components.
3. A mass residual (imbalance) is determined for each node.
4. Node pressure corrections are determined by establishing the system Jacobian matrix from knowledge of the nodal residuals, their rate of change with respect to nodal pressure change and the rate of change of the branch mass flow rates with branch pressure drop (all of which are known at the end of an iteration step).
5. The pressure corrections are applied to the nodal pressures and the next iterative step commenced.
6. The process is terminated when the nodal residuals fall below a prescribed value.

Q4. Describe how the fluid flow within an energy system may be modelled by the computational fluid dynamics (CFD) method.

1. Boundary conditions are represented by the temperature of bounding surfaces and mass & momentum inputs.
2. The system is represented by the discretised Navier-Stokes equations when applied to a finite volume lattice representing the flow domain.
3. Buoyancy is represented by the Boussinesq approximation whereby the fluid density is held constant and the effects of buoyancy are included within the momentum equations.
4. A turbulence transport model is normally used whereby the influence of turbulence on the time averaged motion of the fluid may be determined.
5. An iterative solution procedure is used to solve the energy, momentum and mass equations to give the distribution of pressure, temperature and velocity (and perhaps other parameters such as humidity and contaminant concentration).

An alternative description:

1. Division of the domain into finite volumes, with a finer grid adopted at surface layers.
2. Initial and boundary conditions imposed:
    - initial values of ρ, u_i and θ are required at time $t = 0$ for all domain cells
    - for solid surfaces, 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 is given in terms of the distribution of relevant variables of state
    - at outlets, impose a constant pressure and a zero gradient for velocity, temperature etc.
3. Simultaneous solution of the energy, mass and momentum equations across all domain cells.

Q5. For each method, give one example of a problem that would be best suited to that approach.

1. NN: best suited to the calculation of fluid flow in a network representing building leakage distribution or plant.
2. CFD: best suited to an assessment of room air quality and distribution of comfort parameters.

Q6. Why is it important, in an energy systems modelling context, to re-establish the parameters of the turbulence model at each time step? In your answer identify these parameters.

1. Because energy systems are often non-steady, low Reynolds Number flows occur in which the flow regime may be characterised as weakly turbulent and be moving from laminar flow through the transition zone to fully turbulent.
2. The parameters are the turbulent kinetic energy (k) and its rate of dissipation (ε) throughout the domain; and the shear stress and convective heat transfer at surfaces.

Q7. Assume a single zone with dimensions 6.5 m x 5 m x 3 m high. The zone is air-tight except for three ventilation openings, each positioned at the same height. Two smaller openings are located on the windward side, with a larger opening on the leeward side. The flow-pressure relationship for each opening is given by

$$\dot{m} = C_D\, A \sqrt{2\, \rho\, \Delta P}$$

and the wind pressure on the facade, Pw (Pa), by

$$P_W = C_P\ \tfrac{1}{2}\, \rho\, v^2$$

where,

$\dot{m}$	mass flow rate kg/s
C_D	discharge coefficient kg/s.Pa$^{0.5}$
A	opening area m^2
ρ	air density kg/m^3
ΔP	pressure difference across an opening Pa
C_P	wind pressure coefficient –
v	wind speed m/s

Using the following data,

diameter of smaller openings: 0.1 m C_D: 0.75
diameter of larger opening: 0.5 m   Cp (windward side): 0.6
wind speed: 6m/s   Cp (leeward side): -0.4 ρ: 1.2 kg/m^3

calculate:

i) the air mass flow rate through each ventilation opening;
ii) the pressure inside the zone; and
iii) the air change rate for the zone.

Volume, $V = 97.5\ m^3$

Let m' = mass flow rate; O = opening; P = pressure; and suffixes L, W and I = leeward, windward and internal respectively.

$P_W = 0.6 \text{ x } 0.5 \text{ x } 1.2 \text{ x } 6^2 = 12.96$ Pa; $A_{OW} = 2\ \pi\ (0.05)2 = 0.016m^2$

$P_L = -0.4 \text{ x } 0.5 \text{ x } 1.2 \text{ x } 6^2 = -8.64$ Pa; $A_{OL} = \pi\ (0.25)2 = 0.196\ m^2$

The flow network is given by: P_W (12.96 Pa) -> $0.016\ m^2$ -> P_I -> $0.196\ m^2$ -> P_L (-8.64 Pa)

i) Mass flow rate

By continuity: $m'_W = m'_L = m' = C.A\sqrt{(2\rho\Delta P_x)}$; for x=W or L

On W side: $m' = 0.75 \text{ x } 0.016 \text{ x } \sqrt{(2 \text{ x } 1.2 \text{ x } \Delta P_{W\text{->}I})}$ => $P_W - P_I = 2893.5\ m'^2$ (1)

On L side: $m' = 0.75 \text{ x } 0.196 \text{ x } \sqrt{(2 \text{ x } 1.2 \text{ x } \Delta P_{I\text{->}L})}$ => $P_I - P_L = 19.3\ m'^2$ (2)

Adding eqns (1) and (2): $P_W - P_L = 2902.8\ m'^2$ => $m' = \sqrt{\{(P_W - P_L)/2902.8\}} = 0.085$ kg/s

Therefore, the flow through the large opening is 0.086 kg/s and the flow through each small opening is 0.043 kg/s.

ii) Pressure

From eqn (1): $P_I = P_W - 2893.5\ m'2 = -8.4$ Pa

iii) Air change rate

$v' = m'/\rho = 0.07\ m^3/s$

=> ACR = v' x 3600 /V = 2.65/hr

Q8. The culvert as shown in the figure is to be used to provide free cooling to a building. The air flow is induced by a fan located just before the outlet of the culvert and by wind-driven pressure differences. The fan is assumed to create a constant ΔP of 30 Pa and it may be assumed that the building pressure is 0 Pa.

The flow-pressure relationship for each opening (inlet-outlet) is given by

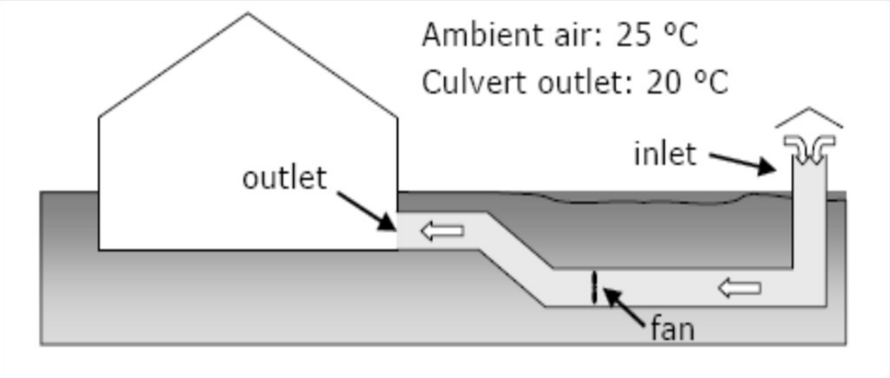
$$\dot{m} = C_D\, A \sqrt{2\, \rho\, \Delta P}$$

and the wind pressure P_W (Pa) at the inlet is given by

$$P_W = C_P\, \tfrac{1}{2}\, \rho\, v^2$$

where

$\dot{m}$	mass flow rate kg/s
C_D	discharge coefficient kg/s.Pa$^{0.5}$
A	opening area m^2
ρ	air density kg/m^3
ΔP	pressure difference across an opening Pa
C_P	wind pressure coefficient –
v	wind speed m/s



Using the data that follows, calculate:

i) the mass flow rate (kg/s) through the culvert;
ii) the pressure before and after the fan (Pa); and
iii) the overall cooling power (W) to result.

Flow coefficient (C_D) for both the inlet and outlet: 0.12
Cp value at inlet: -0.5
Cp value at outlet: 0 (no wind effects)
Air density: 1.2 kg m^3
Air specific heat: 1.1 kJ/kg.C
Wind speed: 5.95 m/s
Culvert diameter: 2 m

Neglecting the pressure drop inside the culvert, there are 4 nodes at different pressure levels:

P_W the wind-induced pressure at the culvert inlet;
P_{bf} the pressure inside the culvert, before the fan;
P_{af} the pressure inside the culvert, after the fan; and
P_B the pressure inside the building.

and the air flow network is given by

$$P_W \xrightarrow{\text{Inlet opening}} P_{bf} \xrightarrow{\text{fan}} P_{af} \xrightarrow{\text{Outlet opening}} P_B$$

The characteristics of the links are:

Inlet opening: $C_D = 0.12$; $A = \pi D^2/4 = 3.14\ m^2$
Fan: constant $\Delta P = 30$ Pa

The wind pressure at the inlet is $P_W = C_P \tfrac{1}{2} \rho v^2 = -0.5*0.5*1.2*5.95^2 = -10.62\,Pa$

The pressure in the building is $P_B = 0$ Pa and P_{af} and P_{bf} are unknown pressures.

i) The flow rates at the inlet and at the outlet are given by

$$\dot{m}_{inlet} = C_D\, A \sqrt{2\,\rho\,\Delta P} = 0.12*(\pi*2^2/4)*\sqrt{2*1.2*(P_w - P_{bf})} \qquad (1)$$

$$\dot{m}_{outlet} = C_D\, A \sqrt{2\,\rho\,\Delta P} = 0.12*(\pi*2^2/4)*\sqrt{2*1.2*(P_{af} - P_B)} \qquad (2)$$

By continuity:

$$\dot{m}_{inlet} = \dot{m}_{outlet} = \dot{m} \qquad (3)$$

Combining eqn (1) and eqn (3):

$$P_w - P_{bf} = \frac{\dot{m}^2}{(0.12*\pi)^2*2*1.2} = \frac{\dot{m}^2}{(0.12*\pi)^2*2*1.2} = \frac{\dot{m}^2}{0.341} \qquad (4)$$

Combining eqn (2) and eqn (3):

$$P_{af} - P_B = \frac{\dot{m}^2}{(0.12*\pi)^2*2*1.2} = \frac{\dot{m}^2}{(0.12*\pi)^2*2*1.2} = \frac{\dot{m}^2}{0.341} \qquad (5)$$

The pressure difference caused by the fan is constant: $P_{af} = 30 + P_{bf}$ (6)

To solve the system formed by eqns (4), (5) and (6), add eqn (4) and eqn (5) and substitute P_{af} according to eqn (6), remembering that $P_W = -10.62$ and $P_B = 0$:

$$P_W - P_{bf} + 30 + P_{bf} - P_B = \frac{2 * \dot{m}^2}{0.341}$$

$$-10.62 + 30 - 0 = \frac{2 * \dot{m}^2}{0.341}$$

$$\dot{m}^2 = 3.304$$

$$=> \boxed{\dot{m} = 1.818 \ kg/s}$$

ii) P_{af} and P_{bf} can be calculated from eqn (4) and eqn (5):

Pressure before the fan, $P_{bf} = -10.62 – 3.304/0.341 = -20.31$ Pa

Pressure after the fan, $P_{af} = 0 + 3.304/0.341 = 9.69$ Pa

iii) The cooling power is $\dot{Q} = \dot{m} C_p \Delta T$ = 1.818*1100*(25-20) = 10000 W