Chapter four The finite volume method for diffusion problems

2.5 Differential and integral forms of the general transport equations

Continuity	$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathbf{u}) = 0$	(2.4)
x-momentum	$\frac{\partial(\rho u)}{\partial t} + \operatorname{div}(\rho u \mathbf{u}) = -\frac{\partial p}{\partial x} + \operatorname{div}(\mu \operatorname{grad} u) + S_{Mx}$	(2.37a)
y-momentum	$\frac{\partial(\rho v)}{\partial t} + \operatorname{div}(\rho v \mathbf{u}) = -\frac{\partial p}{\partial y} + \operatorname{div}(\mu \operatorname{grad} v) + S_{My}$	(2.37b)
z-momentum	$\frac{\partial(\rho w)}{\partial t} + \operatorname{div}(\rho w \mathbf{u}) = -\frac{\partial p}{\partial z} + \operatorname{div}(\mu \operatorname{grad} w) + S_{Mz}$	(2.37c)
Energy	$\frac{\partial(\rho i)}{\partial t} + \operatorname{div}(\rho i \mathbf{u}) = -p \operatorname{div} \mathbf{u} + \operatorname{div}(k \operatorname{grad} T) + \Phi + S_i$	(2.38)
Equations of state	$p = p(\rho, T)$ and $i = i(\rho, T)$	(2.28)
	e.g. perfect gas $p = \rho R T$ and $i = C_v T$	(2.29)

Continuity	$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \mathbf{u}) = 0$	(2.4)
x-momentum	$\frac{\partial (\rho u)}{\partial t} + \mathrm{div}(\rho u \mathbf{u}) = -\frac{\partial p}{\partial x} + \mathrm{div}(\mu \ \mathrm{grad}\ u) + S_{Mx}$	(2.37a)
y-momentum	$\frac{\partial (\rho v)}{\partial t} + \mathrm{div}(\rho v \mathbf{u}) = -\frac{\partial p}{\partial y} + \mathrm{div}(\mu \ \mathrm{grad}\ v) + S_{My}$	(2.37b)
z-momentum	$\frac{\partial (\rho w)}{\partial t} + \mathrm{div}(\rho w \mathbf{u}) = -\frac{\partial p}{\partial z} + \mathrm{div}(\mu \ \mathrm{grad}\ w) + S_{Mz}$	(2.37c)
Energy	$\frac{\partial (\rho i)}{\partial t} + \mathrm{div}(\rho i \mathbf{u}) = -p \ \mathrm{div}\ \mathbf{u} + \mathrm{div}(k \ \mathrm{grad}\ T) + \Phi + S_i$	(2.38)

$$\frac{\partial (\rho \phi)}{\partial t} + \mathrm{div}(\rho \phi \mathbf{u}) = \mathrm{div}(\Gamma \ \mathrm{grad}\ \phi) + S_\phi$$

$$\frac{\partial(\rho\phi)}{\partial t} + \operatorname{div}(\rho\phi\mathbf{u}) = \operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi$$

Rate of increase of ϕ of fluid element	+	Net rate of flow of ϕ out of fluid element	=	Rate of increase of ϕ due to diffusion	+	Rate of increase of ϕ due to sources

$$\frac{\partial(\rho\phi)}{\partial t} + \mathrm{div}(\rho\phi\mathbf{u}) = \mathrm{div}(\Gamma \ \mathrm{grad}\ \phi) + S_\phi$$

$$\int_{\mathrm{CV}} \frac{\partial(\rho\phi)}{\partial t}\mathrm{d}V + \int_{\mathrm{CV}} \mathrm{div}(\rho\phi\mathbf{u})\mathrm{d}V = \int_{\mathrm{CV}} \mathrm{div}(\Gamma \ \mathrm{grad}\ \phi)\mathrm{d}V + \int_{\mathrm{CV}} S_\phi \mathrm{d}V$$

$$\frac{\partial(\rho\phi)}{\partial t} + \mathrm{div}(\rho\phi\mathbf{u}) = \mathrm{div}(\Gamma \,\mathrm{grad}\, \phi) + S_\phi$$

$$\int_{CV} \frac{\partial(\rho\phi)}{\partial t}\mathrm{d}V + \int_{CV} \mathrm{div}(\rho\phi\mathbf{u})\mathrm{d}V = \int_{CV} \mathrm{div}(\Gamma \,\mathrm{grad}\, \phi)\mathrm{d}V + \int_{CV} S_\phi \mathrm{d}V$$

$$\int_{CV} \mathrm{div}(\mathbf{a})\mathrm{d}V = \int_{A} \mathbf{n} \,.\, \mathbf{a}\mathrm{d}A$$

$$\frac{\partial(\rho\phi)}{\partial t} + \operatorname{div}(\rho\phi\mathbf{u}) = \operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi$$

$$\int_{CV} \frac{\partial(\rho\phi)}{\partial t} \mathrm{d}V + \int_{CV} \operatorname{div}(\rho\phi\mathbf{u})\mathrm{d}V = \int_{CV} \operatorname{div}(\Gamma \operatorname{grad} \phi)\mathrm{d}V + \int_{CV} S_\phi \mathrm{d}V$$

$$\frac{\partial}{\partial t}\left(\int_{CV} \rho\phi dV\right) + \int_A \mathbf{n} . (\rho\phi\mathbf{u})\mathrm{d}A = \int_A \mathbf{n} . (\Gamma \operatorname{grad} \phi)\mathrm{d}A + \int_{CV} S_\phi \mathrm{d}V$$

$$\int_{CV} \operatorname{div}(\mathbf{a})\mathrm{d}V = \int_A \mathbf{n} . \mathbf{a}\mathrm{d}A$$

$$\frac{\partial}{\partial t}\left(\int_{CV} \rho\phi dV\right) + \int_A \mathbf{n} . (\rho\phi\mathbf{u})\mathrm{d}A = \int_A \mathbf{n} . (\Gamma \operatorname{grad} \phi)\mathrm{d}A + \int_{CV} S_\phi \mathrm{d}V$$

Rate of increase of ϕ inside the control volume	+	Net rate of decrease of ϕ due to convection across the control volume boundaries	=	Net rate of increase of ϕ due to diffusion across the control volume boundaries	+	Net rate of creation of ϕ inside the control volume

$$\frac{\partial(\rho\phi)}{\partial t} + \operatorname{div}(\rho\phi\mathbf{u}) = \operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi$$

Chapter four The finite volume method for diffusion problems

$$\frac{\partial(\rho\phi)}{\partial t} + \operatorname{div}(\rho\phi\mathbf{u}) = \operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi$$

Chapter four The finite volume method for diffusion problems

$$\frac{\partial(\rho\phi)}{\partial t} + \operatorname{div}(\rho\phi\mathbf{u}) = \operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi$$

0

0

Chapter four The finite volume method for diffusion problems

$$\frac{\partial(\rho\phi)}{\partial t} + \operatorname{div}(\rho\phi\mathbf{u}) = \operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi$$

0 0

$$\operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi = 0$$

$$\mathrm{div}(\Gamma\ \mathrm{grad}\ \phi) + S_\phi = 0$$

$$\mathrm{div}(\Gamma \ \mathrm{grad}\ \phi) + S_\phi = 0$$

The control volume integration, which forms the key step of the finite volume method that distinguishes it from all other CFD techniques, yields the following form:

$$\int_{CV} \mathrm{div}(\Gamma \ \mathrm{grad}\ \phi)\mathrm{d}V + \int_{CV} S_\phi \mathrm{d}V = \int_{A} \mathbf{n} \,.\, (\Gamma \ \mathrm{grad}\ \phi)\mathrm{d}A + \int_{CV} S_\phi \mathrm{d}V = 0 \qquad (4.2)$$

$$\mathrm{div}(\Gamma\ \mathrm{grad}\ \phi) + S_\phi = 0$$

The control volume integration, which forms the key step of the finite volume method that distinguishes it from all other CFD techniques, yields the following form:

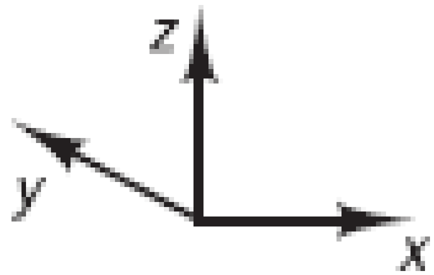
$$\int_{CV} \mathrm{div}(\Gamma\ \mathrm{grad}\ \phi)\mathrm{d}V + \int_{CV} S_\phi \mathrm{d}V$$

$$= \int_{A} \mathbf{n} \,.\, (\Gamma\ \mathrm{grad}\ \phi)\mathrm{d}A + \int_{CV} S_\phi \mathrm{d}V = 0 \tag{4.2}$$

Net rate of increase of ϕ due to diffusion across the control volume boundaries	+	Net rate of creation of ϕ inside the control volume

4.2 Finite volume method for one-dimensional steady state diffusion

4.2 Finite volume method for one-dimensional steady state diffusion



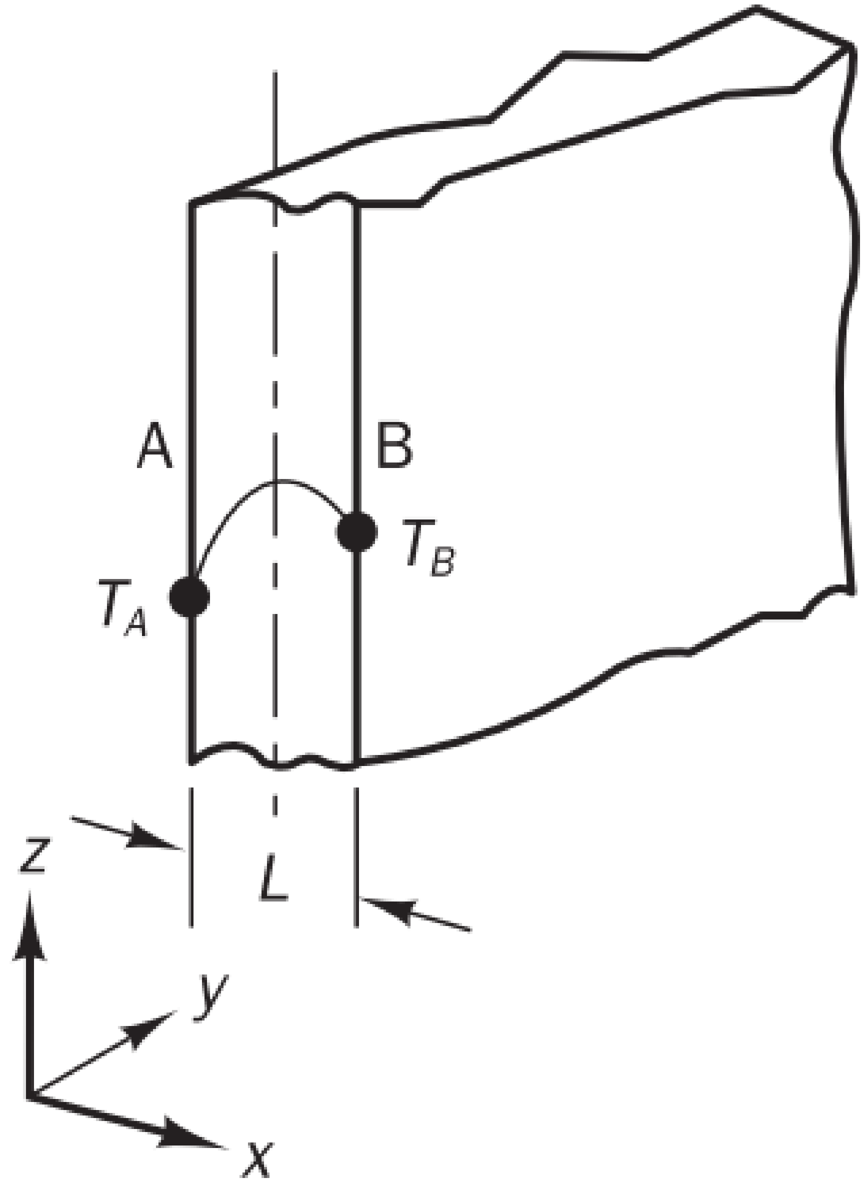
$$\mathrm{div}(\Gamma \,\mathrm{grad}\, \phi) + S_\phi = 0$$

4.2 Finite volume method for one-dimensional steady state diffusion

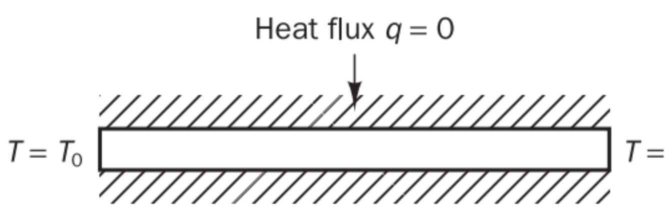
$$\operatorname{div}(\Gamma \operatorname{grad} \phi) + S_\phi = 0$$

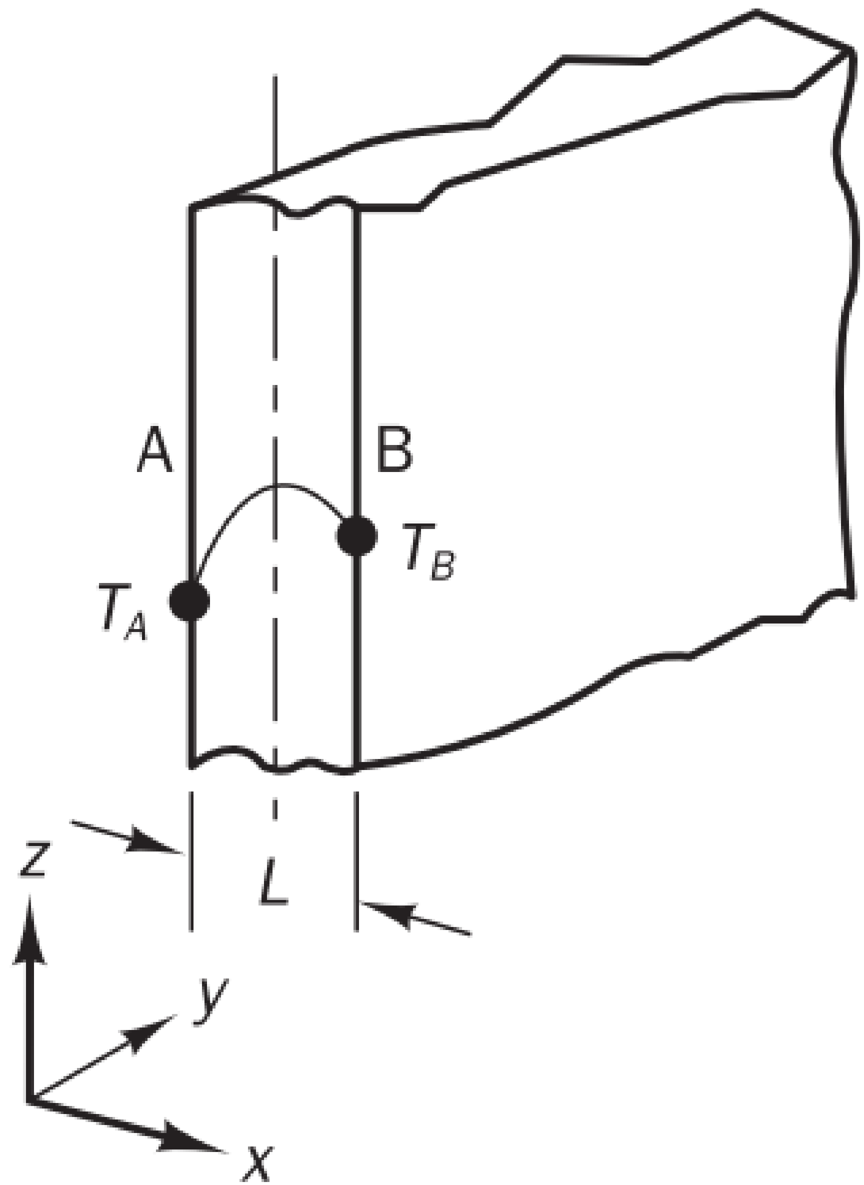
$$\frac{d}{dx}\left(\Gamma \frac{d\phi}{dx}\right) + S = 0$$

4.2 Finite volume method for one-dimensional steady state diffusion

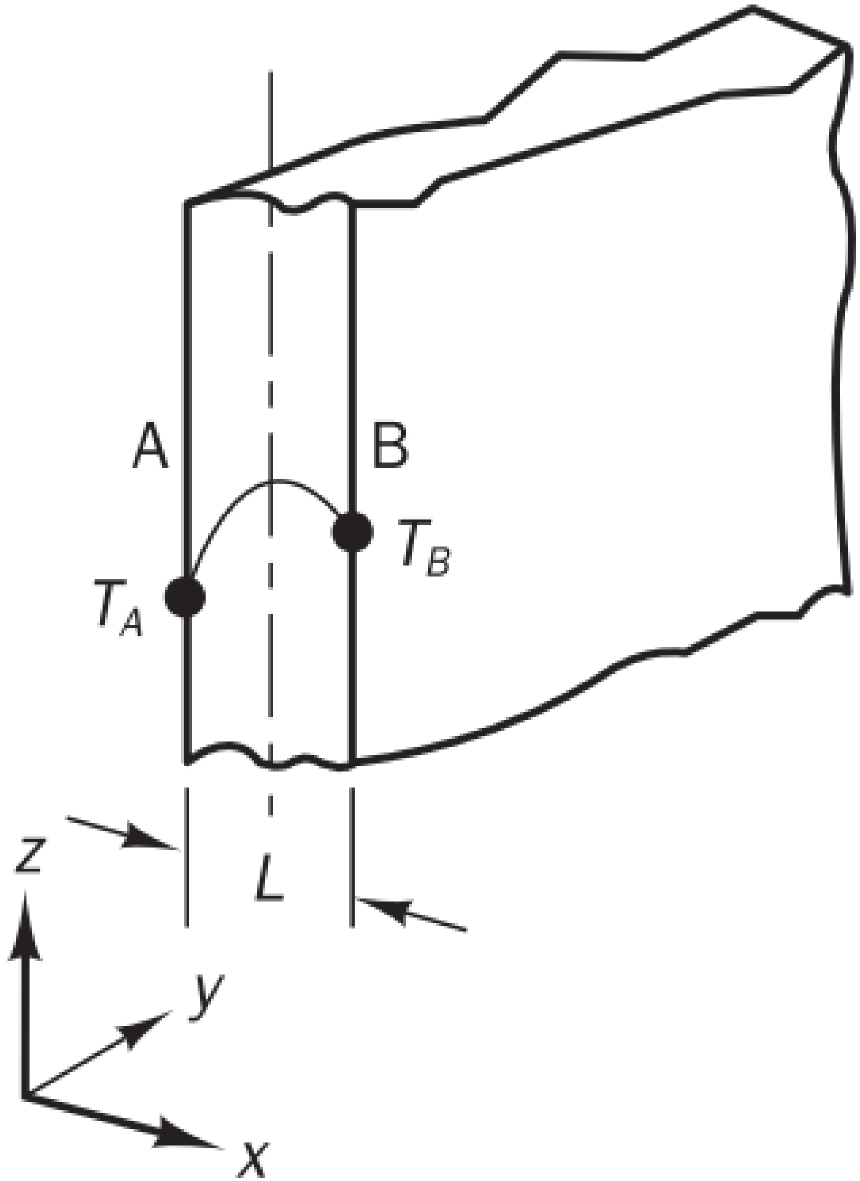


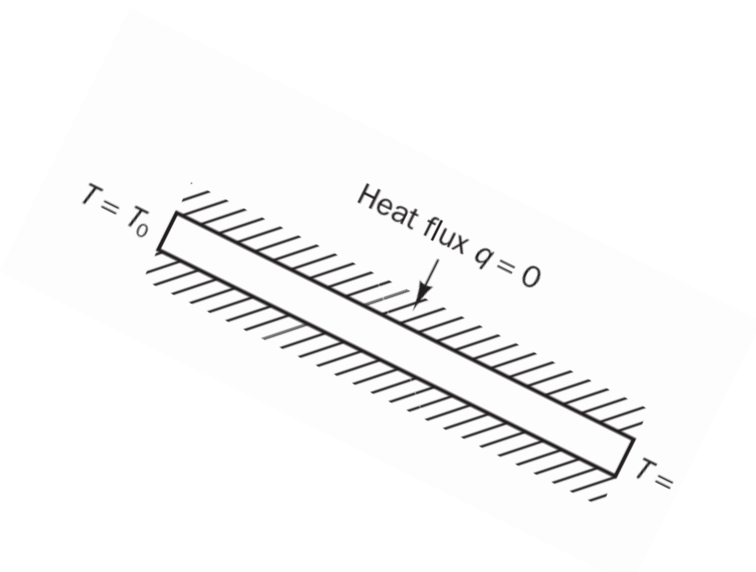
4.2 Finite volume method for one-dimensional steady state diffusion



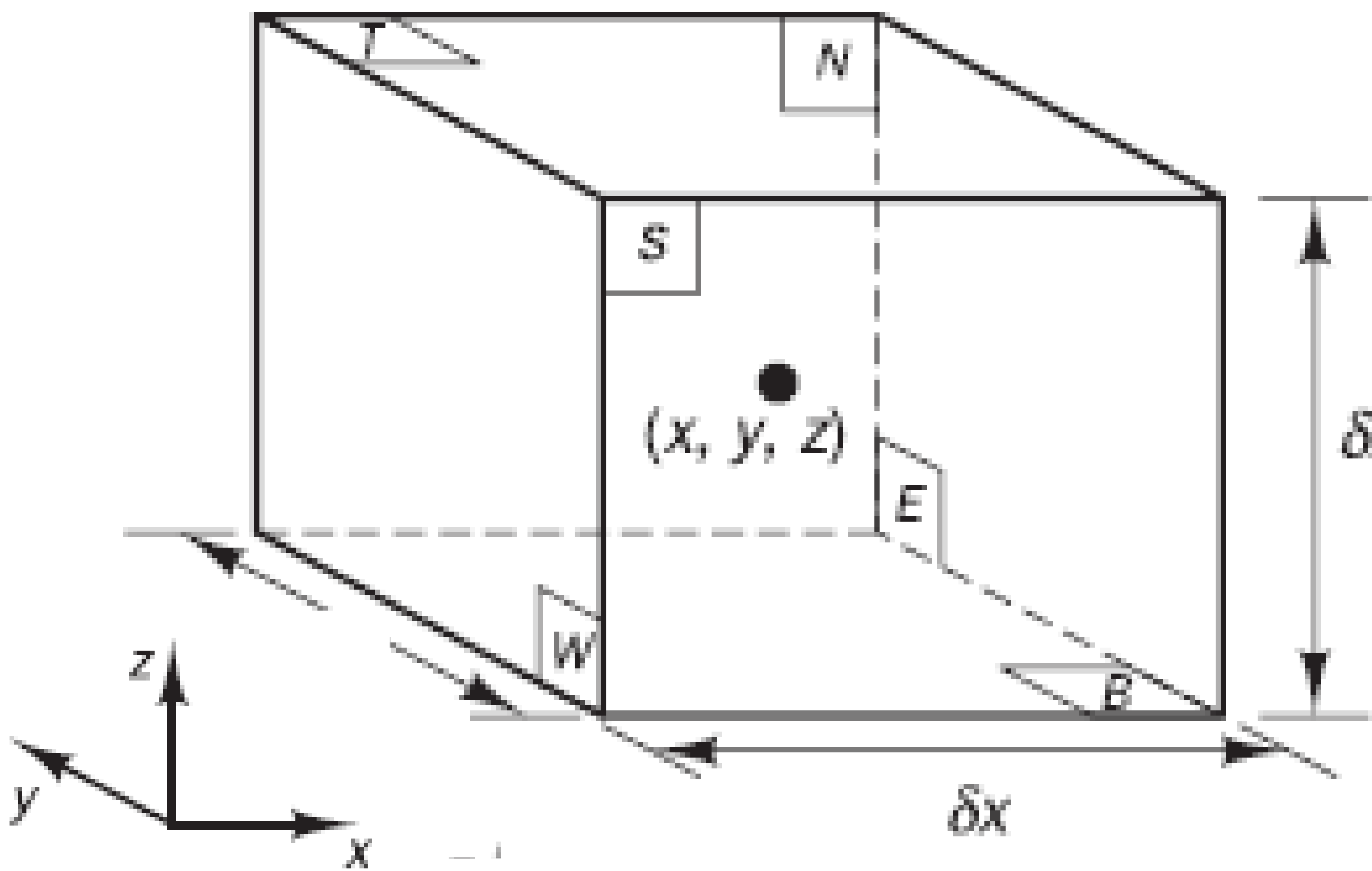


4.2 Finite volume method for one-dimensional steady state diffusion

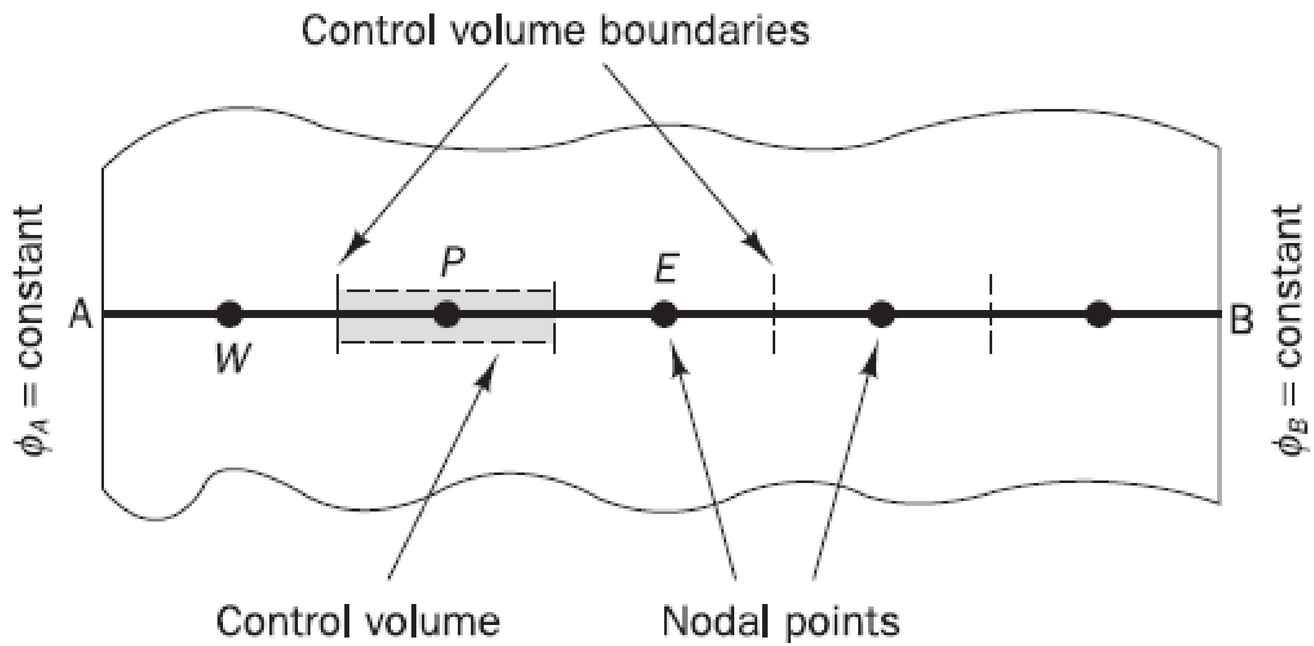




4.2 Finite volume method for one-dimensional steady state diffusion

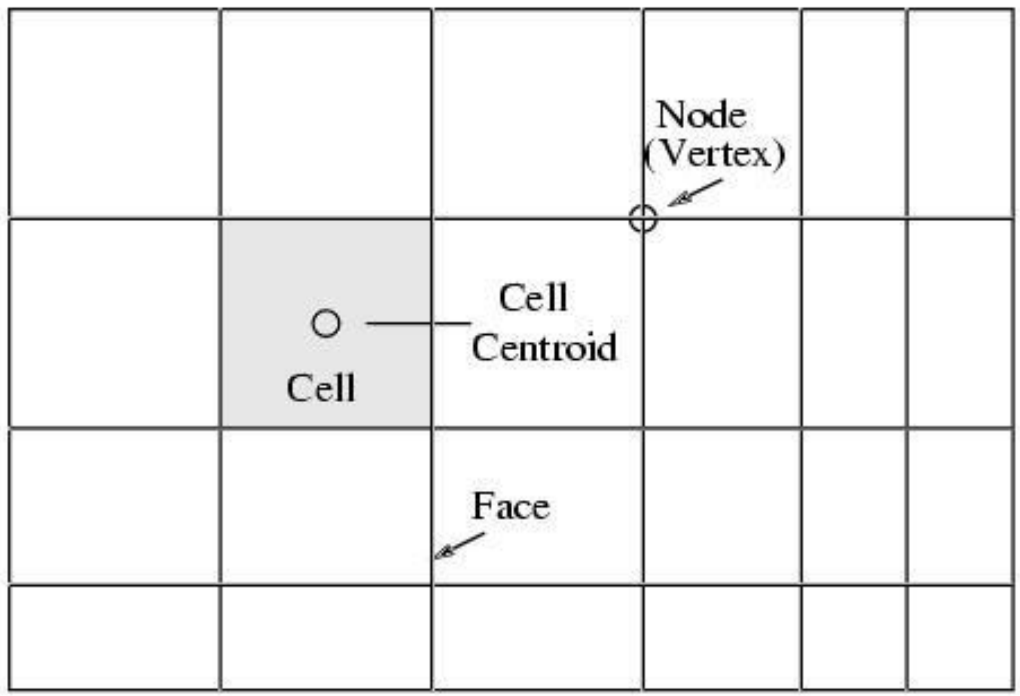


4.2 Finite volume method for one-dimensional steady state diffusion



Step 1: Grid generation

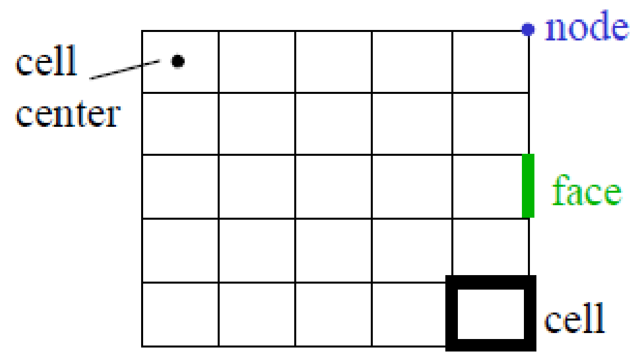
Mesh Terminology



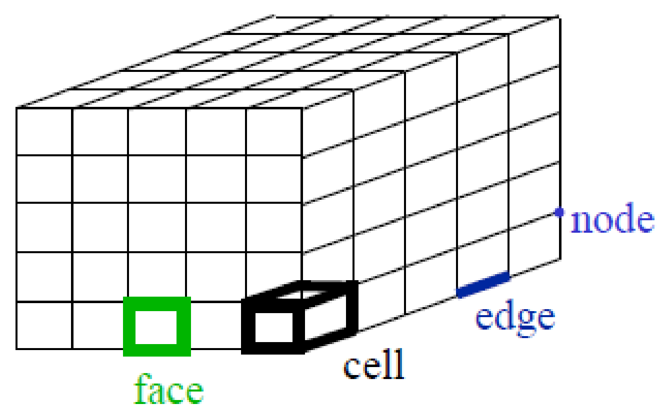
- *Node-based finite volume scheme*: φ stored at vertex
- *Cell-based finite volume scheme*: φ stored at cell centroid

Terminology

- Cell = control volume into which domain is broken up.
- Node = grid point.
- Cell center = center of a cell.
- Edge = boundary of a face.
- Face = boundary of a cell.
- Zone = grouping of nodes, faces, and cells:
  - Wall boundary zone.
  - Fluid cell zone.
- Domain = group of node, face and cell zones.



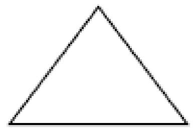
2D computational grid



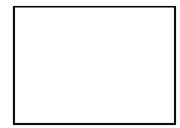
3D computational grid

Typical cell shapes

- Many different cell/element and grid types are available. Choice depends on the problem and the solver capabilities.
- Cell or element types:
  - 2D:

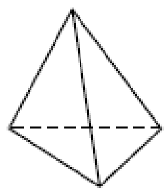


triangle (“**tri**”)

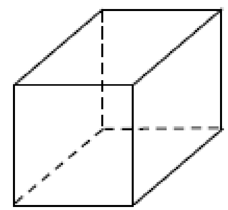


2D prism (**quadrilateral** or “**quad**”)

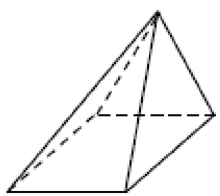
  - 3D:



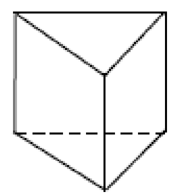
tetrahedron (“**tet**”)



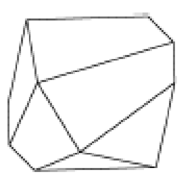
prism with quadrilateral base (**hexahedron** or “**hex**”)



pyramid

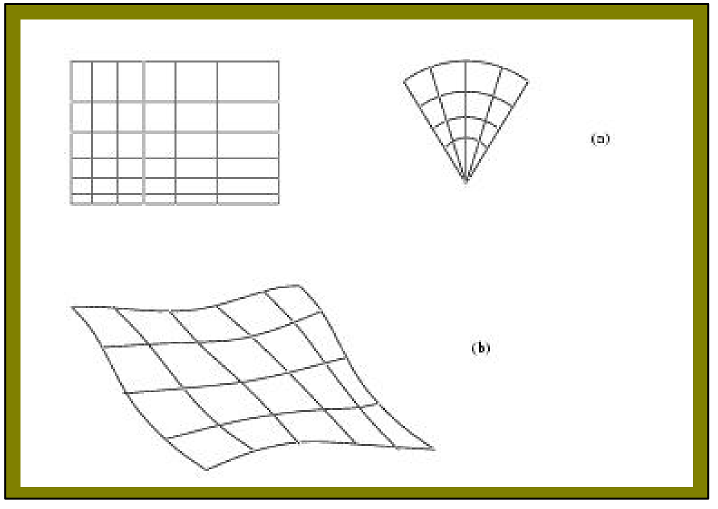


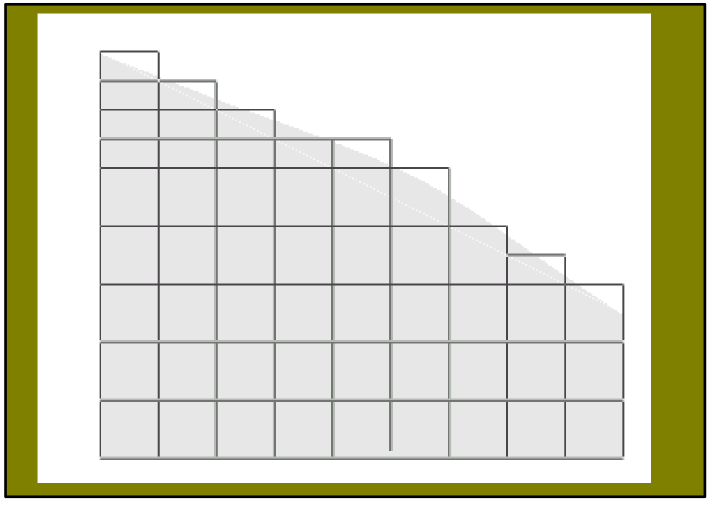
prism with triangular base (**wedge**)



arbitrary polyhedron

Mesh Types

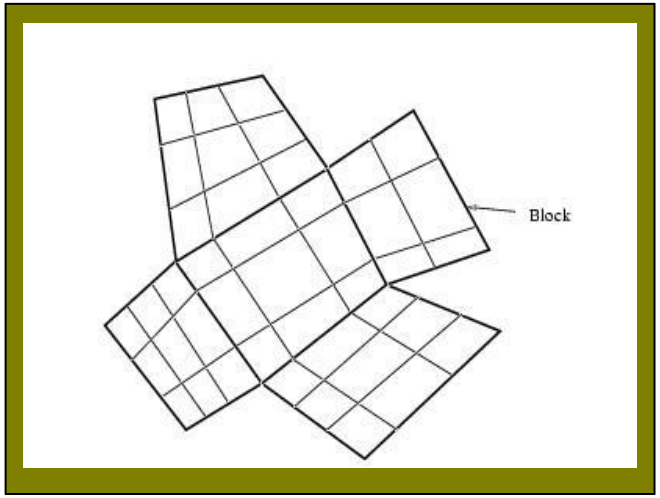




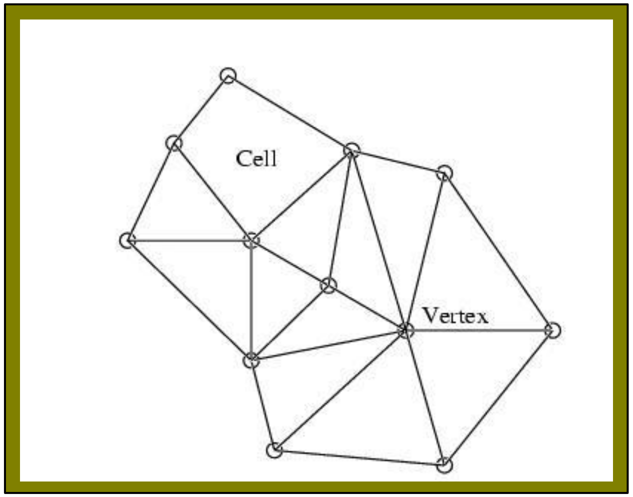
Regular and body-fitted meshes

Stair-stepped representation of complex geometry

Mesh types (cont'd)



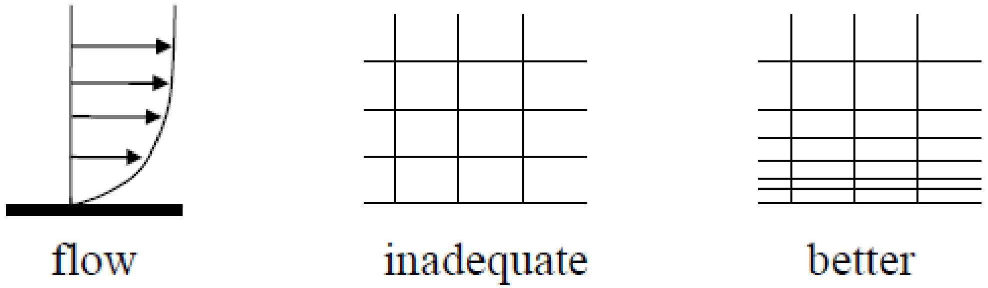
Block-structured meshes



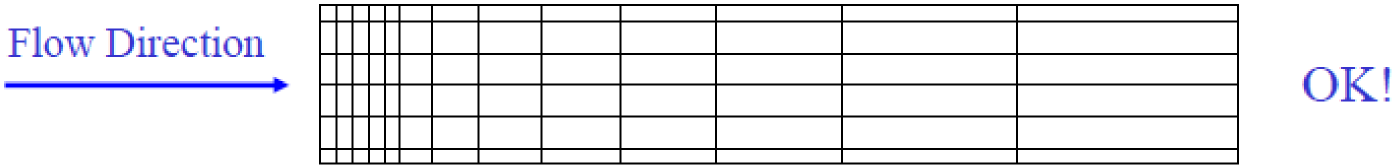
Unstructured meshes

Grid design guidelines: resolution

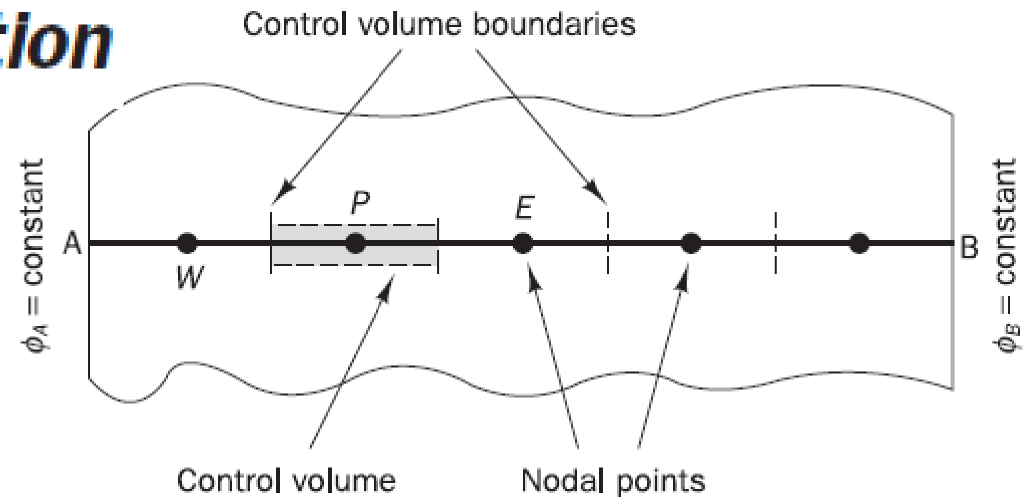
- Pertinent flow features should be adequately resolved.

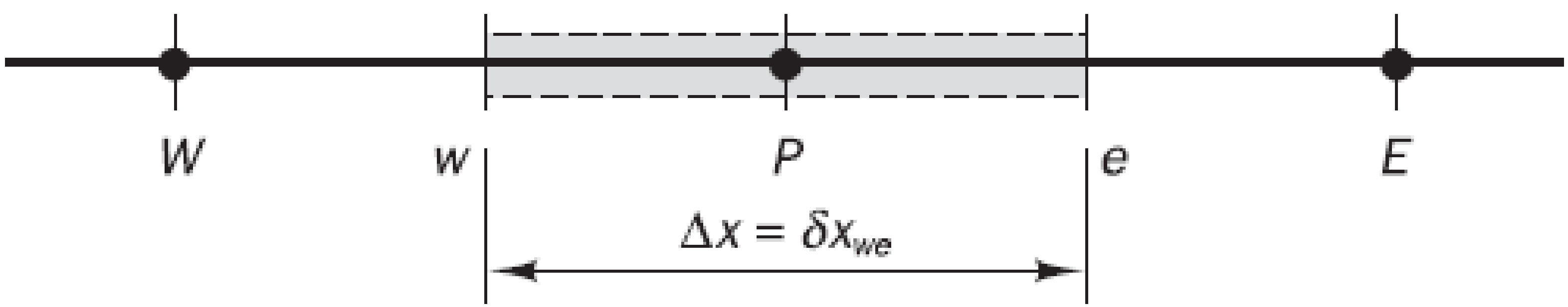


- Cell aspect ratio (width/height) should be near one where flow is multi-dimensional.
- Quad/hex cells can be stretched where flow is fully-developed and essentially one-dimensional.

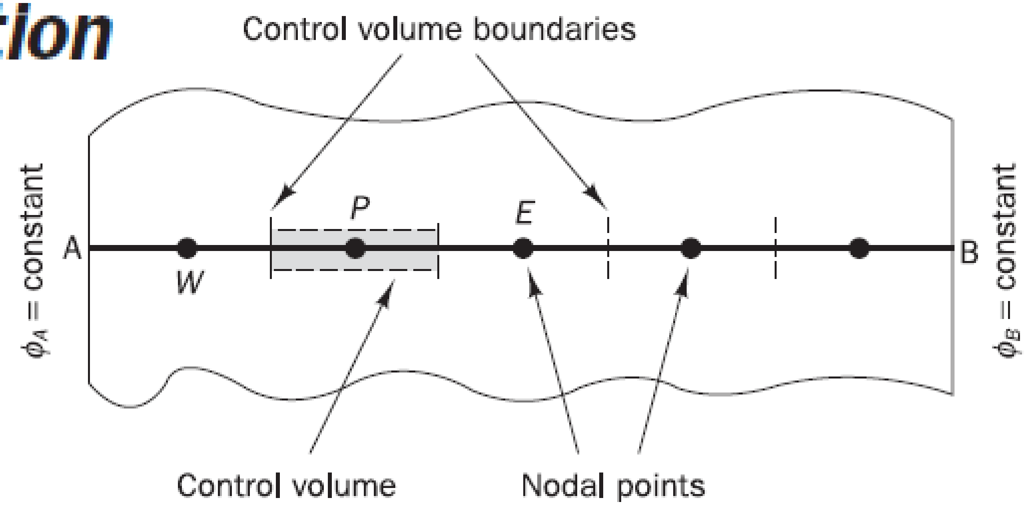


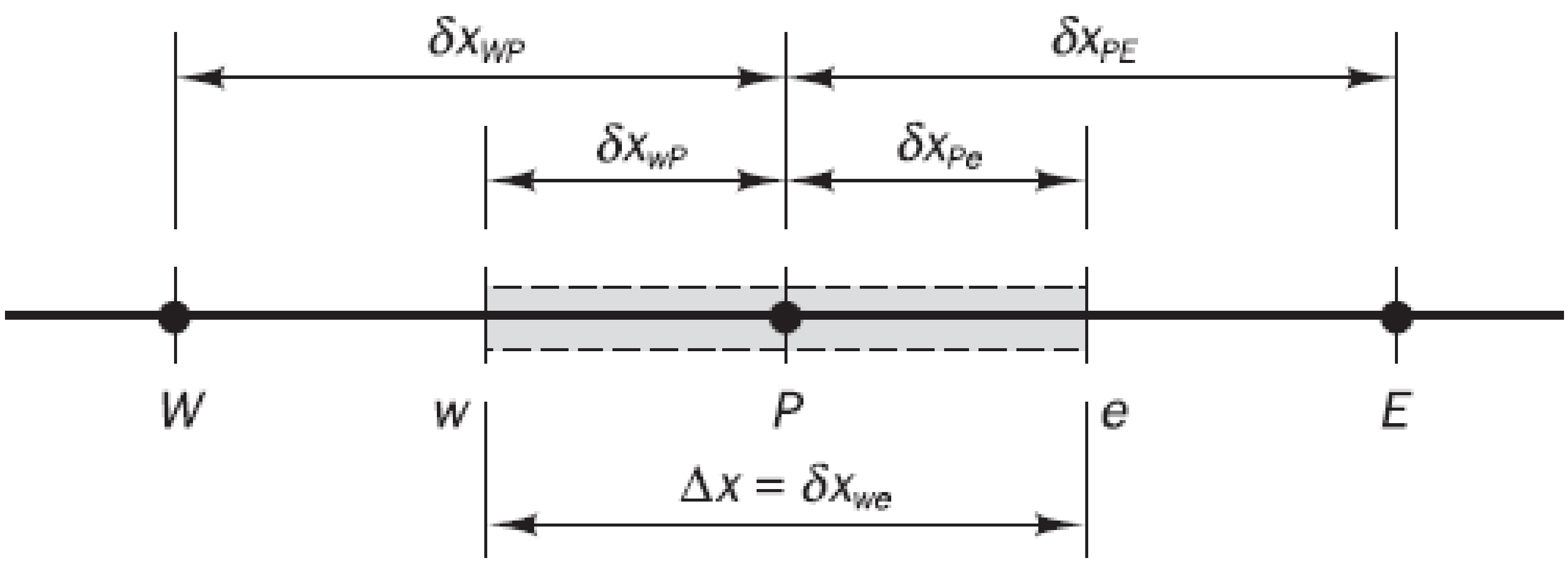
Step 1: Grid generation





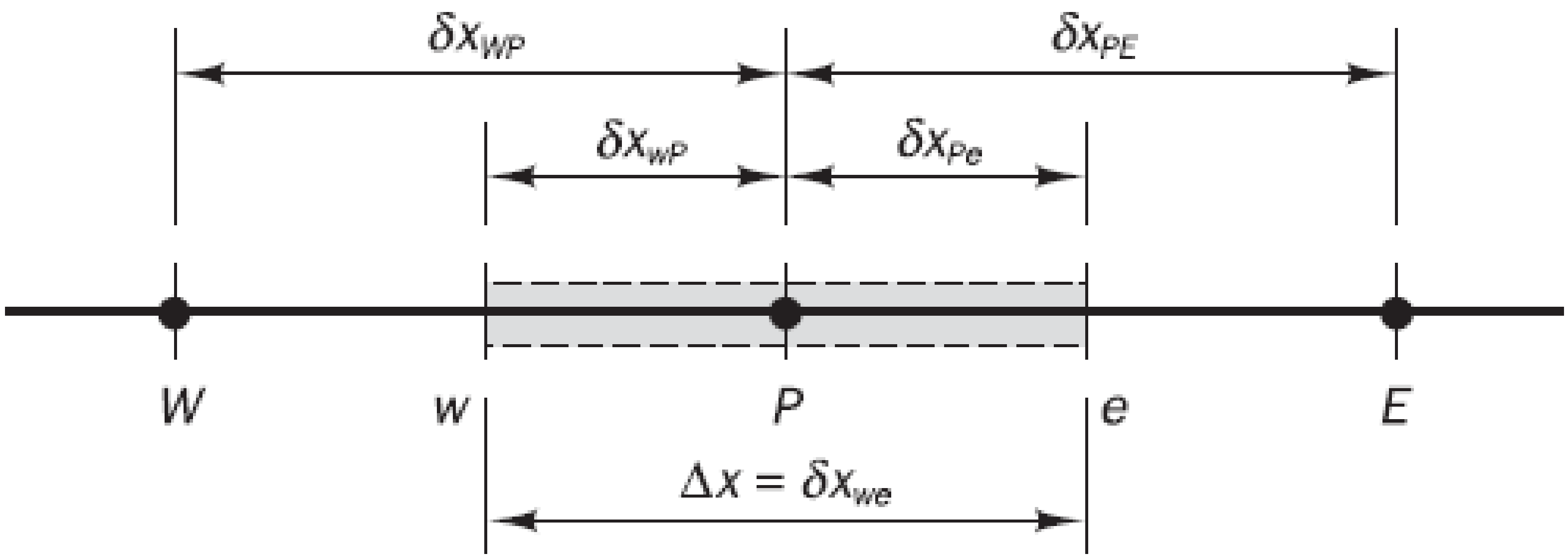
Step 1: Grid generation





Step 2: Discretisation

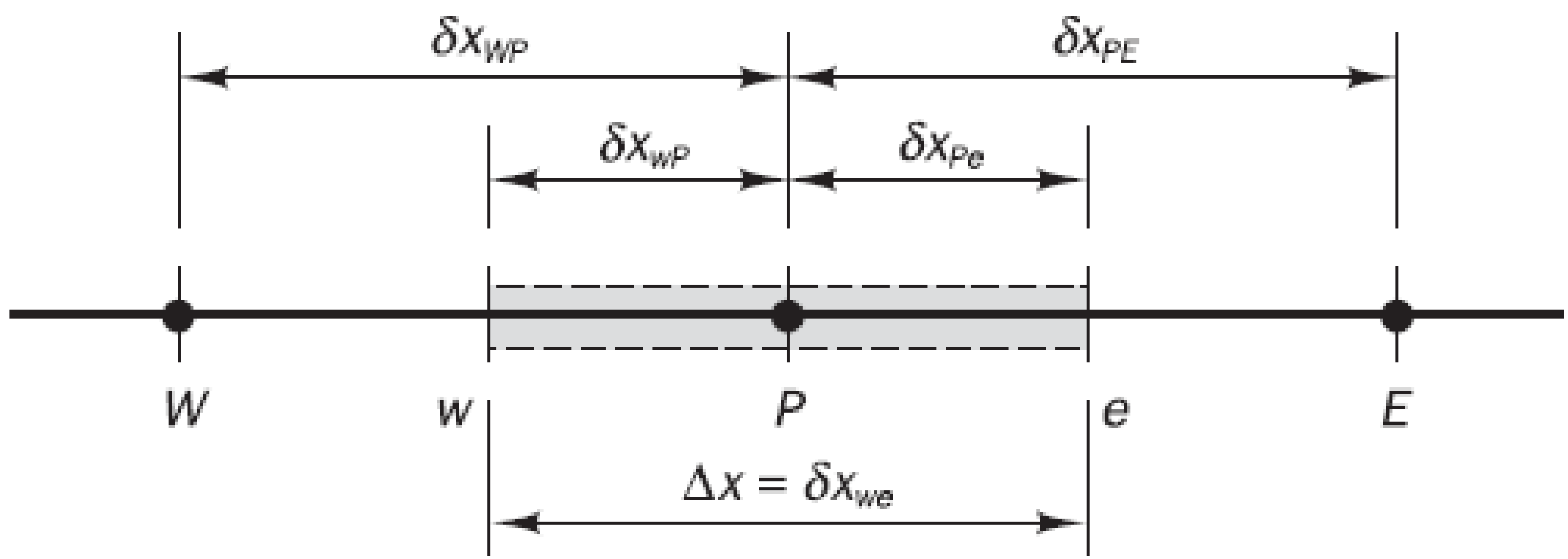
$$\frac{d}{dx}\left(\Gamma\frac{d\phi}{dx}\right)+S=0$$



Step 2: Discretisation

$$\int_{\Delta V} \frac{d}{dx}\left(\Gamma \frac{d\phi}{dx}\right) dV + \int_{\Delta V} S\, dV = \left(\Gamma A \frac{d\phi}{dx}\right)_e - \left(\Gamma A \frac{d\phi}{dx}\right)_w + \bar{S}\Delta V = 0 \qquad (4.4)$$

Here A is the cross-sectional area of the control volume face, ΔV is the volume and $\bar{S}$ is the average value of source S over the control volume. It is



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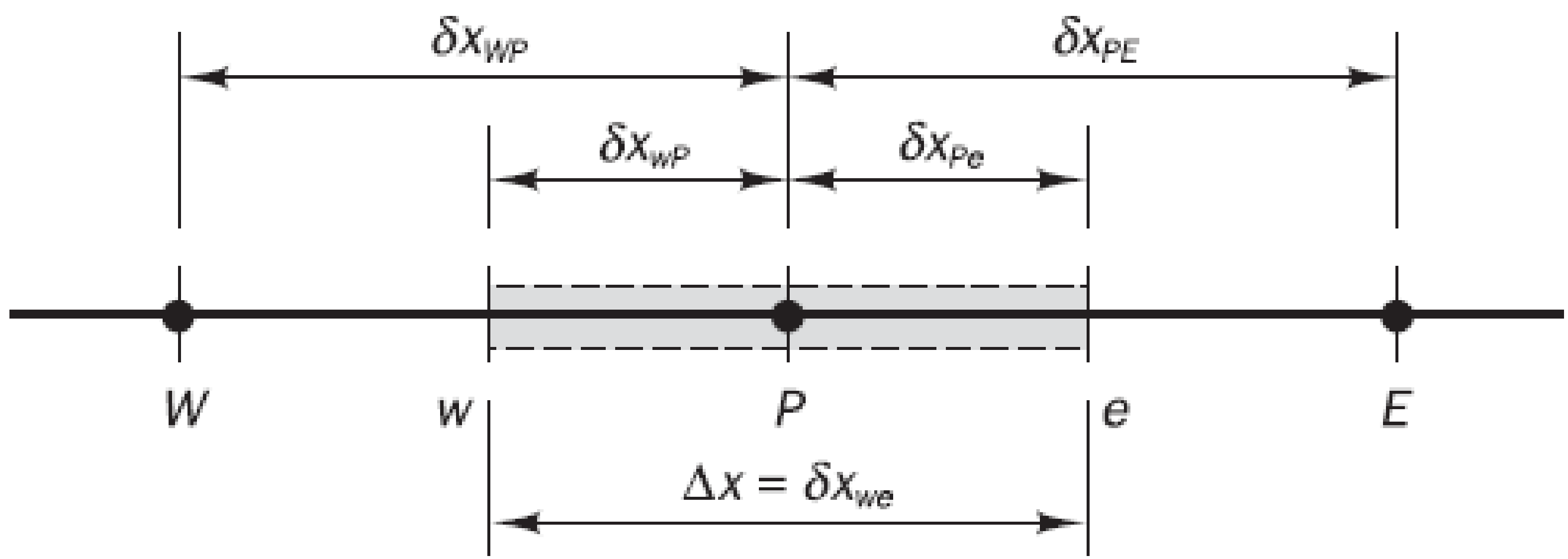

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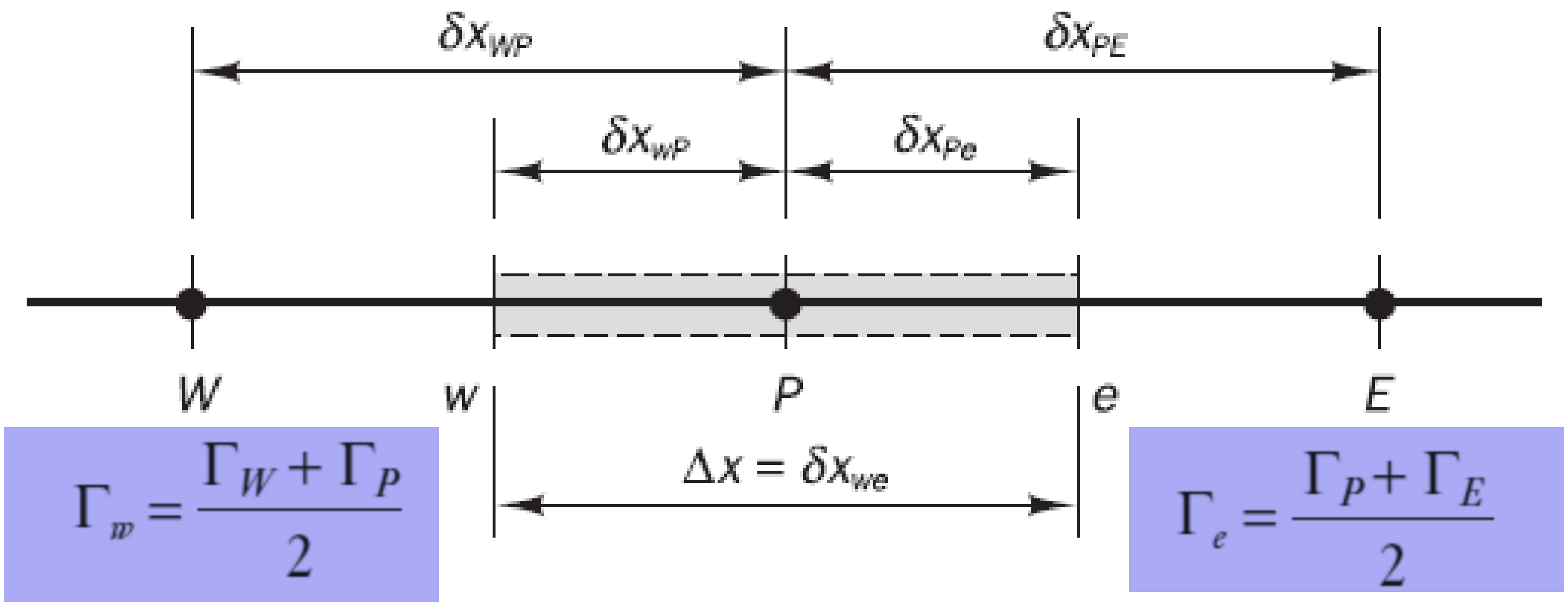


$$\Gamma_w = \frac{\Gamma_W + \Gamma_P}{2}$$

$$\Gamma_e = \frac{\Gamma_P + \Gamma_E}{2}$$

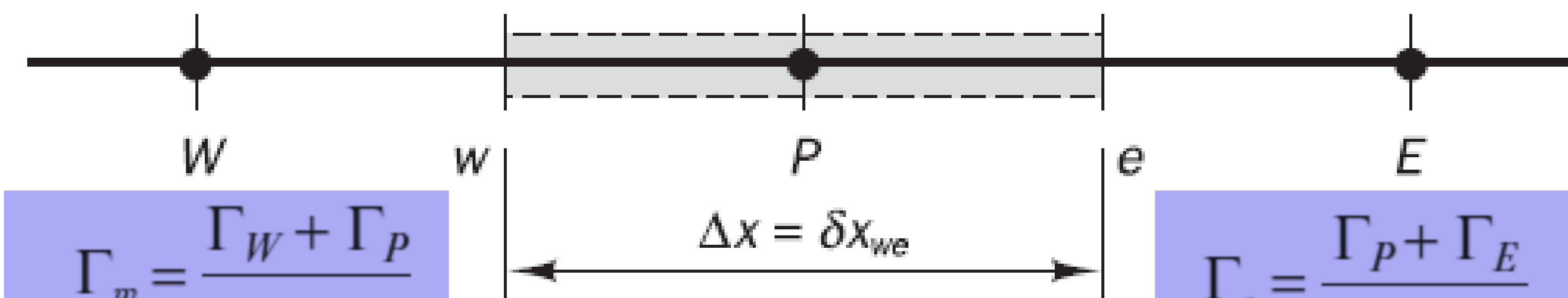
Step 2: Discretisation

$$\int_{\Delta V} \frac{d}{dx}\left(\Gamma \frac{d\phi}{dx}\right) dV + \int_{\Delta V} S\, dV = \left(\Gamma A \frac{d\phi}{dx}\right)_e - \left(\Gamma A \frac{d\phi}{dx}\right)_w + \bar{S}\Delta V = 0 \qquad (4.4)$$

And the diffusive flux terms are evaluated as

$$\left(\Gamma A \frac{d\phi}{dx}\right)_e = \Gamma_e A_e \left(\frac{\phi_E - \phi_P}{\delta x_{PE}}\right)$$

$$\left(\Gamma A \frac{d\phi}{dx}\right)_w = \Gamma_w A_w \left(\frac{\phi_P - \phi_W}{\delta x_{WP}}\right)$$



$$\Gamma_w = \frac{\Gamma_W + \Gamma_P}{2}$$

$$\Gamma_e = \frac{\Gamma_P + \Gamma_E}{2}$$

Step 2: Discretisation

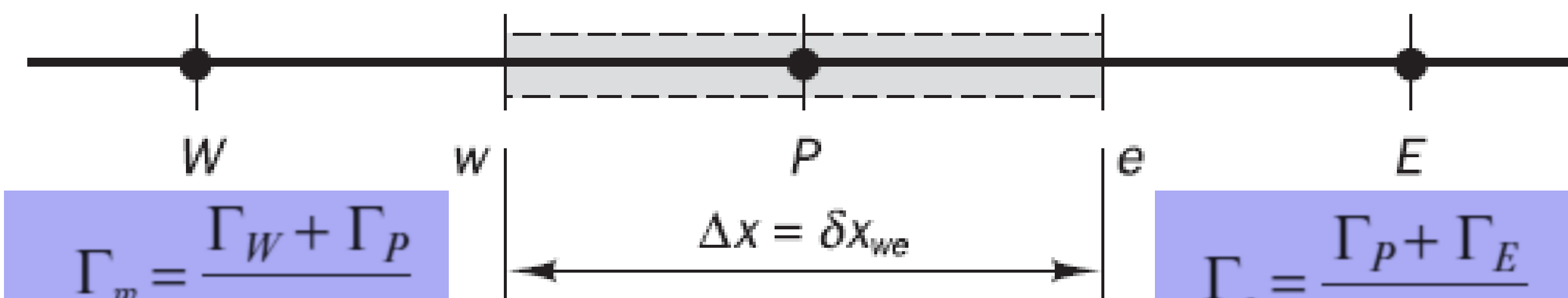
$$\int_{\Delta V} \frac{d}{dx}\left(\Gamma \frac{d\phi}{dx}\right) dV + \int_{\Delta V} S\,dV = \left(\Gamma A \frac{d\phi}{dx}\right)_e - \left(\Gamma A \frac{d\phi}{dx}\right)_w + \bar{S}\Delta V = 0 \qquad (4.4)$$

$$\bar{S}\Delta V = S_u + S_p \phi_P$$

And the diffusive flux terms are evaluated as

$$\left(\Gamma A \frac{d\phi}{dx}\right)_e = \Gamma_e A_e \left(\frac{\phi_E - \phi_P}{\delta x_{PE}}\right)$$

$$\left(\Gamma A \frac{d\phi}{dx}\right)_w = \Gamma_w A_w \left(\frac{\phi_P - \phi_W}{\delta x_{WP}}\right)$$



$$\Gamma_w = \frac{\Gamma_W + \Gamma_P}{2}$$

$$\Gamma_e = \frac{\Gamma_P + \Gamma_E}{2}$$

Step 2: Discretisation

$$\int_{\Delta V} \frac{d}{dx}\left(\Gamma \frac{d\phi}{dx}\right) dV + \int_{\Delta V} S\, dV = \left(\Gamma A \frac{d\phi}{dx}\right)_e - \left(\Gamma A \frac{d\phi}{dx}\right)_w + \bar{S}\Delta V = 0 \qquad (4.4)$$

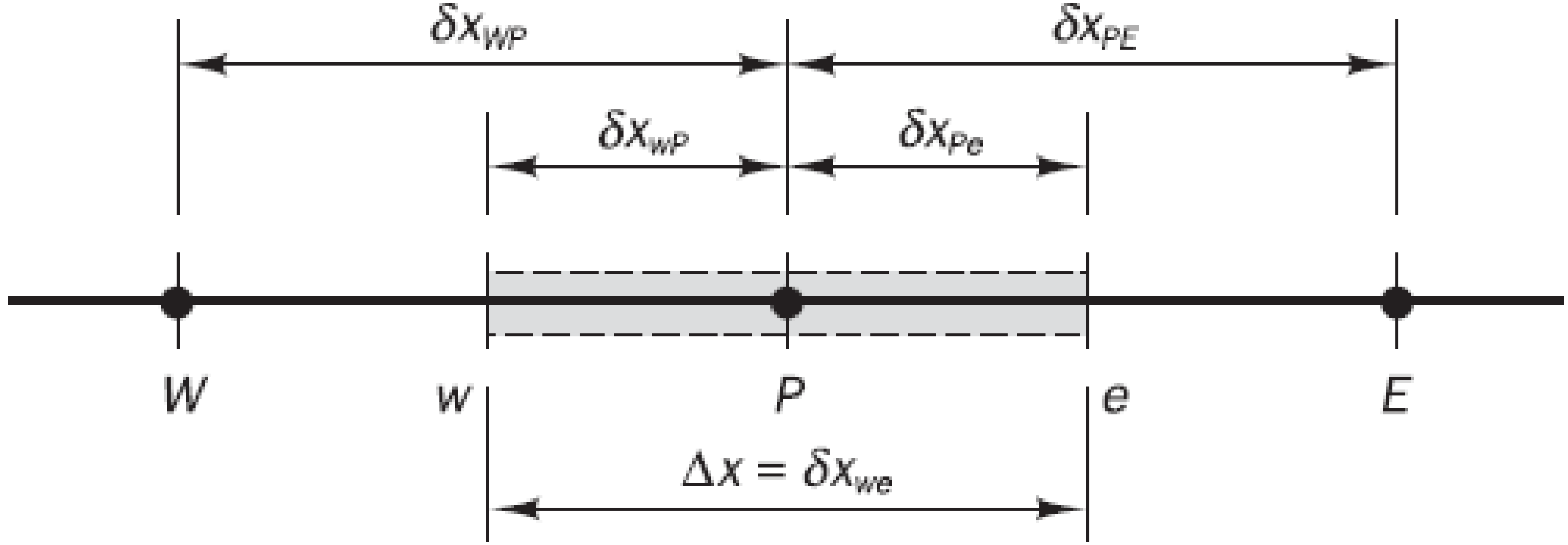
Substitution of equations (4.6), (4.7) and (4.8) into equation (4.4) gives

$$\Gamma_e A_e \left(\frac{\phi_E - \phi_P}{\delta x_{PE}}\right) - \Gamma_w A_w \left(\frac{\phi_P - \phi_W}{\delta x_{WP}}\right) + (S_u + S_p \phi_P) = 0 \qquad (4.9)$$

This can be rearranged as

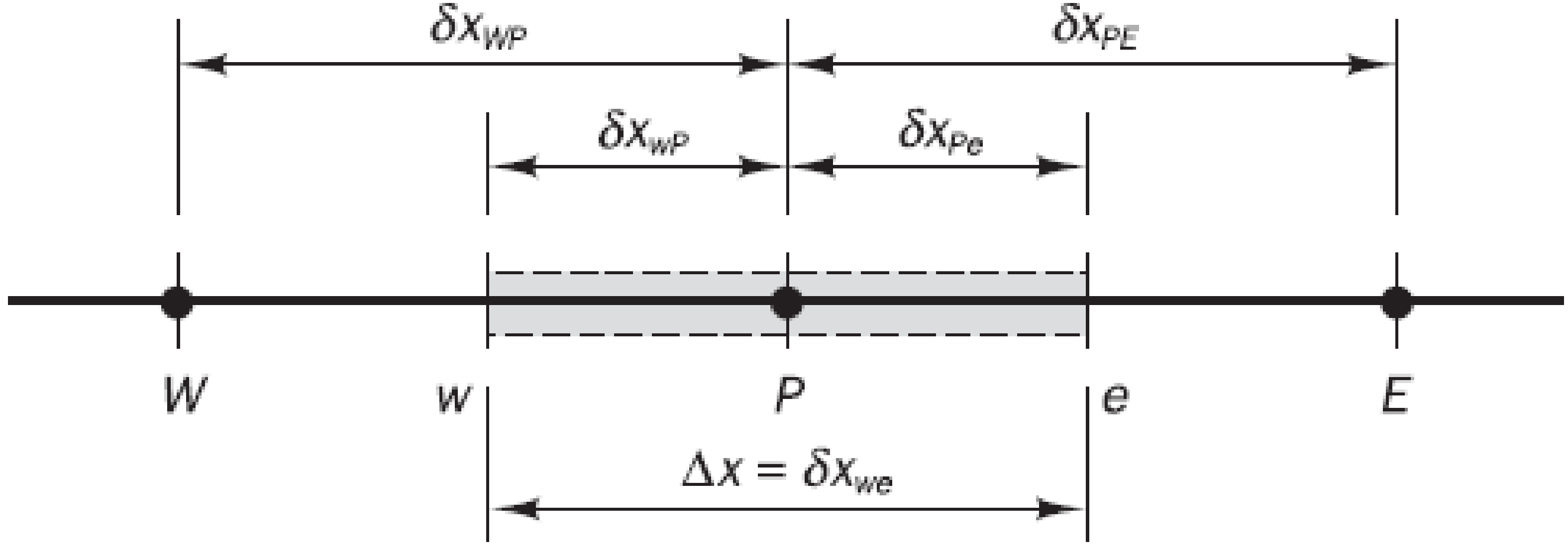
$$\boxed{\left(\frac{\Gamma_e}{\delta x_{PE}} A_e + \frac{\Gamma_w}{\delta x_{WP}} A_w - S_p\right)\phi_P = \left(\frac{\Gamma_w}{\delta x_{WP}} A_w\right)\phi_W + \left(\frac{\Gamma_e}{\delta x_{PE}} A_e\right)\phi_E + S_u} \qquad (4.10)$$

Step 2: Discretisation



$$\left(\frac{\Gamma_e}{\delta x_{PE}}A_e + \frac{\Gamma_w}{\delta x_{WP}}A_w - S_p\right)\phi_P = \left(\frac{\Gamma_w}{\delta x_{WP}}A_w\right)\phi_W + \left(\frac{\Gamma_e}{\delta x_{PE}}A_e\right)\phi_E + S_u \quad (4.10)$$

Step 2: Discretisation



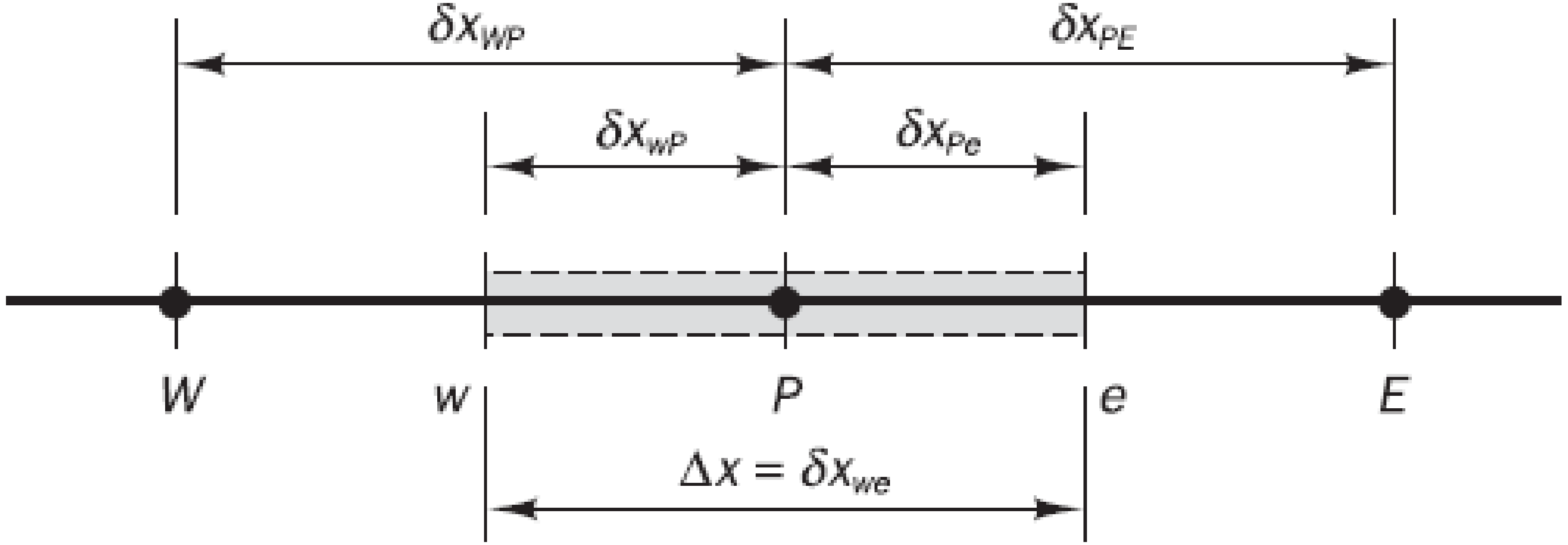
$$\left(\frac{\Gamma_e}{\delta x_{PE}}A_e + \frac{\Gamma_w}{\delta x_{WP}}A_w - S_p\right)\phi_P = \left(\frac{\Gamma_w}{\delta x_{WP}}A_w\right)\phi_W + \left(\frac{\Gamma_e}{\delta x_{PE}}A_e\right)\phi_E + S_u \qquad (4.10)$$

$$a_P\phi_P = a_W\phi_W + a_E\phi_E + S_u$$

Step 2: Discretisation

$$a_P \phi_P = a_W \phi_W + a_E \phi_E + S_u$$

a_W	a_E	a_P
$\frac{\Gamma_w}{\delta x_{WP}} A_w$	$\frac{\Gamma_e}{\delta x_{PE}} A_e$	$a_W + a_E - S_P$



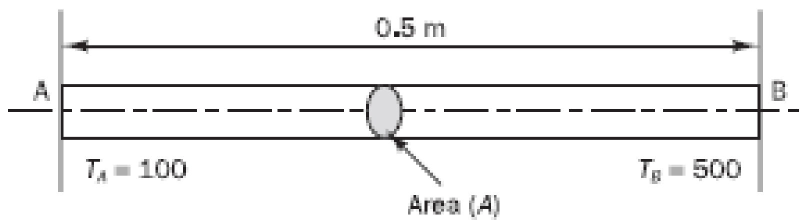
- Step III: Solution of Equation
  - Direct Method
  - Iterative Method

In Chapter 7 we describe matrix solution methods that are specially designed for CFD procedures. The techniques of dealing with different types of boundary conditions will be examined in detail in Chapter 9.

Diffusion Problems

Example I: Consider the problem of source-free heat conduction in an insulated rod whose ends are maintained at constant temperatures of 100°C and 500°C respectively. The one- dimensional problem sketched in Figure is governed by:

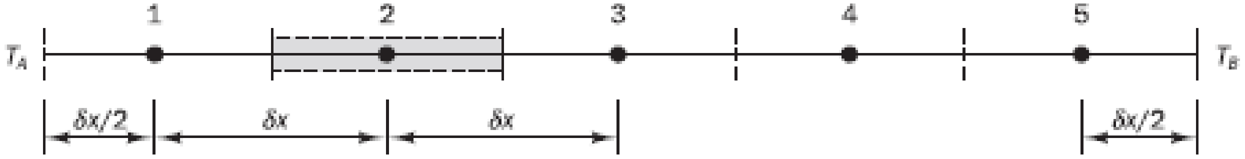
$$\frac{d}{dx}\left(k\frac{dT}{dx}\right) = 0$$



- Calculate the steady state temperature distribution in the rod. Thermal conductivity *k* equals 1000 W/m.K, cross-sectional area A is 10×10^{-3} m^2.

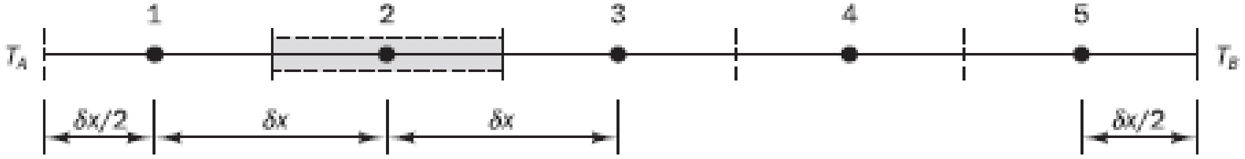
Diffusion Problems

- Let us divide the length of the rod into five equal control volumes as shown in Figure ($\delta x = 0.1$ m).



Diffusion Problems

- Let us divide the length of the rod into five equal control volumes as shown in Figure (δx = 0.1 m).



- For each one of nodes 2, 3 and 4 temperature values to the east and west are available as nodal values.

$$\left(\frac{k_e}{\delta x_{PE}}A_e+\frac{k_w}{\delta x_{WP}}A_w\right)T_P=\left(\frac{k_w}{\delta x_{WP}}A_w\right)T_W+\left(\frac{k_e}{\delta x_{PE}}A_e\right)T_E$$

Diffusion Problems

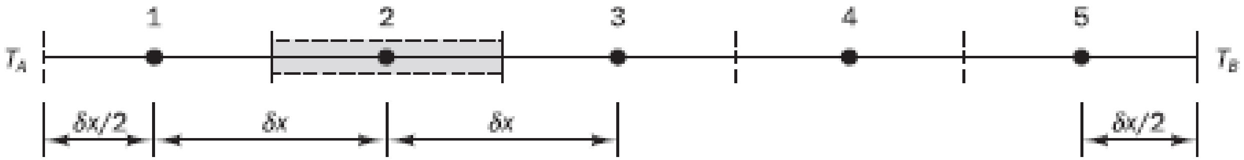
- The thermal conductivity ($k_e = k_w = k$), node spacing (δx) and cross-sectional area ($A_e = A_w = A$) are constants. Therefore the discretised equation for nodal points 2, 3 and 4 is:

$$a_P T_P = a_W T_W + a_E T_E$$

a_W	a_E	a_P
$\frac{k}{\delta x} A$	$\frac{k}{\delta x} A$	$a_W + a_E$

- S_u and S_p are zero in this case since there is no source term in the governing equation

Diffusion Problems



- Nodes 1 and 5 are boundary nodes, and therefore require special attention.
- For node 1:

$$kA\left(\frac{T_E - T_P}{\delta x}\right) - kA\left(\frac{T_P - T_A}{\delta x/2}\right) = 0$$

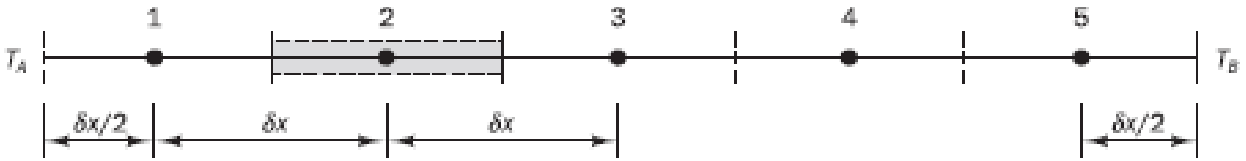
$$\left(\frac{k}{\delta x}A + \frac{2k}{\delta x}A\right)T_P = 0\ .\ T_W + \left(\frac{k}{\delta x}A\right)T_E + \left(\frac{2k}{\delta x}A\right)T_A$$

- Discretised equation for boundary node 1:

$$a_P T_P = a_W T_W + a_E T_E + S_u$$

a_W	a_E	a_P	S_P	S_u
0	$\frac{kA}{\delta x}$	$a_W + a_E - S_p$	$-\frac{2kA}{\delta x}$	$\frac{2kA}{\delta x}T_A$

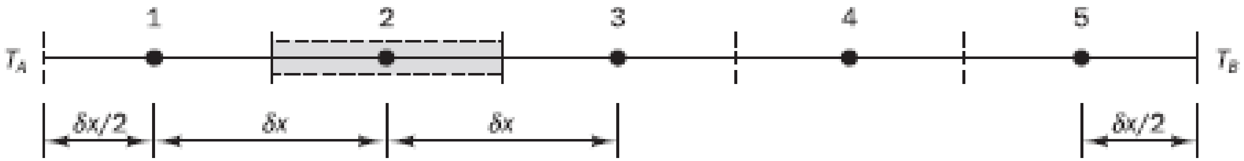
Diffusion Problems



- Discretised equation for boundary node 5:

$$kA\left(\frac{T_B - T_P}{\delta x/2}\right) - kA\left(\frac{T_P - T_W}{\delta x}\right) = 0 \qquad (4.19)$$

Diffusion Problems



$$\left(\frac{k}{\delta x}A + \frac{2k}{\delta x}A\right)T_P = \left(\frac{k}{\delta x}A\right)T_W + 0\ .\ T_E + \left(\frac{2k}{\delta x}A\right)T_B \qquad (4.20)$$

The **discretised equation for boundary node 5** is

$$\boxed{a_P T_P = a_W T_W + a_E T_E + S_u} \qquad (4.21)$$

where

a_W	a_E	a_P	S_P	S_u
$\frac{kA}{\delta x}$	0	$a_W + a_E - S_p$	$-\frac{2kA}{\delta x}$	$\frac{2kA}{\delta x}T_B$

Diffusion Problems

a_W	a_E	a_P	S_P	S_u
0	$\frac{kA}{\delta x}$	$a_W + a_E - S_p$	$-\frac{2kA}{\delta x}$	$\frac{2kA}{\delta x} T_A$

a_W	a_E	a_P
$\frac{k}{\delta x} A$	$\frac{k}{\delta x} A$	$a_W + a_E$

a_W	a_E	a_P	S_P	S_u
$\frac{kA}{\delta x}$	0	$a_W + a_E - S_p$	$-\frac{2kA}{\delta x}$	$\frac{2kA}{\delta x} T_B$

Diffusion Problems

a_W	a_E	a_P	S_P	S_u
0	$\frac{kA}{\delta x}$	$a_W + a_E - S_p$	$-\frac{2kA}{\delta x}$	$\frac{2kA}{\delta x}T_A$

a_W	a_E	a_P
$\frac{k}{\delta x}A$	$\frac{k}{\delta x}A$	$a_W + a_E$

a_W	a_E	a_P	S_P	S_u
$\frac{kA}{\delta x}$	0	$a_W + a_E - S_p$	$-\frac{2kA}{\delta x}$	$\frac{2kA}{\delta x}T_B$

- For kA/δx = 100 is:

$$300T_1 = 100T_2 + 200T_A$$
$$200T_2 = 100T_1 + 100T_3$$
$$200T_3 = 100T_2 + 100T_4$$
$$200T_4 = 100T_3 + 100T_5$$
$$300T_5 = 100T_4 + 200T_B$$

Diffusion Problems

Node	a_W	a_E	S_u	S_P	$a_P = a_W + a_E - S_P$
1	0	100	$200T_A$	−200	300
2	100	100	0	0	200
3	100	100	0	0	200
4	100	100	0	0	200
5	100	0	$200T_B$	−200	300

Diffusion Problems

Node	a_W	a_E	S_u	S_P	$a_P = a_W + a_E - S_P$
1	0	100	$200T_A$	−200	300
2	100	100	0	0	200
3	100	100	0	0	200
4	100	100	0	0	200
5	100	0	$200T_B$	−200	300

$$\begin{bmatrix} 300 & -100 & 0 & 0 & 0 \\ -100 & 200 & -100 & 0 & 0 \\ 0 & -100 & 200 & -100 & 0 \\ 0 & 0 & -100 & 200 & -100 \\ 0 & 0 & 0 & -100 & 300 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \end{bmatrix} = \begin{bmatrix} 200T_A \\ 0 \\ 0 \\ 0 \\ 200T_B \end{bmatrix}$$

Diffusion Problems

- For $T_A = 100$ and $T_B = 500$ the solution of equation can obtained by using, for example, Gaussian elimination:

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \end{bmatrix} = \begin{bmatrix} 140 \\ 220 \\ 300 \\ 380 \\ 460 \end{bmatrix}$$

Diffusion Problems

- For $T_A = 100$ and $T_B = 500$ the solution of equation can obtained by using, for example, Gaussian elimination:

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