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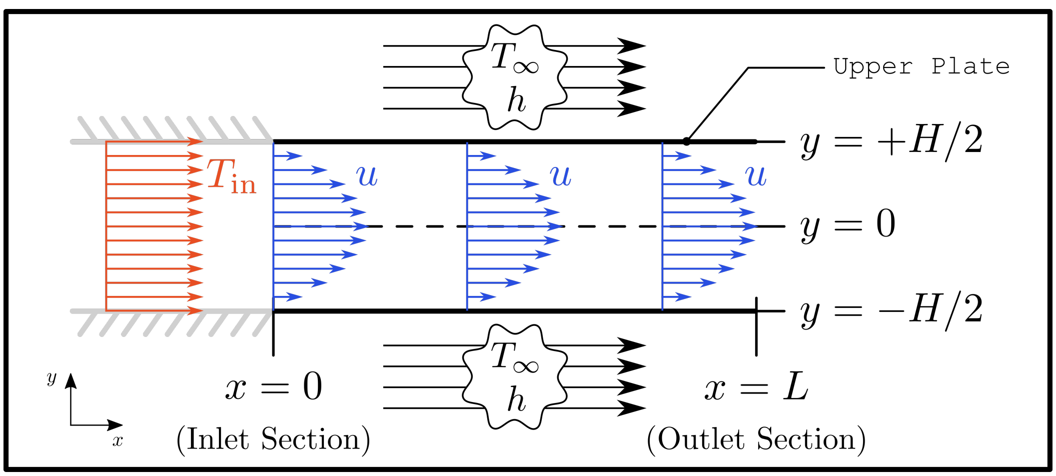
Advanced Heat Transfer

Exam 2 – Problem 3

July 13, 2021 (15h00)

Consider simultaneous diffusion and convection transport of thermal energy in a planar channel formed by two parallel plates at rest – see figure. The channel height, *i.e.*, the distance between the two plates (H) and the channel length (L) are equal to 0.1 m and 0.5 m, respectively. A laminar flow of an incompressible and constant property fluid under fully developed hydrodynamic conditions is considered in the entire channel. The axial velocity profile is given by $u(y) = 1.5u_m \left[1 - 4(y/H)^2\right]$, where y and u_m correspond to the local $y-$position measured from the channel mid-plane and mean fluid velocity, respectively. (Note that for the current conditions, the $y-$velocity component (v) and $\partial u/\partial x$ are negligible.) At the channel inlet section ($x = 0$), a uniform fluid temperature profile equal to 600°C (T_{in}) is considered. Heat losses from the channel are considered through the plates (located at $y = \pm H/2$) to an adjoining fluid circulating at the external channel side at a temperature of 50°C (T_∞) and with a convection heat transfer coefficient equal to $50\,\text{W}\,\text{m}^{-2}\,\text{K}^{-1}$ (h). (Neglect the thickness of the plates.) The density (ρ), specific heat (c_p), and thermal conductivity (k) of the fluid circulating in the channel are equal to $0.4611\,\text{kg}\,\text{m}^{-3}$, $1098\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$, and $0.05714\,\text{W}\,\text{m}^{-1}\,\text{K}^{-1}$, respectively. Temperature gradients along the third Cartesian coordinate (direction z) are negligible and, consequently, the governing equation for temperature distribution is formulated as presented below.

$$\rho c_p \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}(\rho u c_p T) + \frac{\partial}{\partial y}(\rho v c_p T) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)$$



Consider the two-dimensional calculation domain discretized by a uniform mesh with $\Delta x = \Delta y = 1$ mm. Apply the finite volume method for the following questions.

(a) (1.0 v.) Determine the range for the mean fluid velocity (u_m) that ensures physically realistic results with the application of the central differencing scheme.

Solution:

To avoid physically unrealistic results the absolute value of the grid Peclet number in the flow direction must be lower than 2. (Absolute grid Peclet numbers below 2 ensures that neighboring node coefficients (a_{nb}) are always positive with the application of the central differencing scheme.) For the current conditions, the flow direction is exclusively along the $x-$axis. Since the fluid velocity profile is not flat (uniform), the maximum fluid velocity should be considered to determine the maximum mean fluid velocity value allowed – see Equation (1).

$$|Pe_x| < 2 \Leftrightarrow \left|\frac{F_x}{D_x}\right| < 2 \Leftrightarrow \frac{\rho u_{\max}}{\Gamma_x/\Delta x} < 2 \Leftrightarrow \frac{\rho u_{\max}\Delta x}{k/c_p} < 2 \Leftrightarrow \frac{\rho u_{\max} c_p \Delta x}{k} < 2 \tag{1}$$

The maximum fluid velocity – registered in the first layer of cells next to the channel mid-plane, particularly at $y_{\mathrm{P}} = 0 + \Delta y/2$ – as a function of the mean fluid velocity is given by Equation (2).

$$\begin{gathered} u_{\max} \equiv u\left(\Delta y/2\right) = 1.5u_m \left[1 - 4\left(\frac{\Delta y/2}{H}\right)^2\right] \Leftrightarrow \\ \Leftrightarrow u_{\max} = 1.5u_m \left[1 - 4 \times \left(\frac{0.001/2}{0.1}\right)^2\right] \Leftrightarrow u_{\max} \approx 1.500u_m \end{gathered} \tag{2}$$

Substituting Equation (2) in Equation (1) and replacing the parameters and properties by the corresponding values the maximum mean fluid velocity value is computed – see Equation (3).

$$\begin{gathered} \frac{\rho u_{\max} c_p \Delta x}{k} < 2 \Leftrightarrow \frac{1.5\rho u_m c_p \Delta x}{k} < 2 \Leftrightarrow u_m < \frac{2k}{1.5\rho c_p \Delta x} \Leftrightarrow \\ \Leftrightarrow u_m < \frac{2 \times 0.05714}{1.5 \times 0.4611 \times 1098 \times 0.001} \Leftrightarrow \boxed{u_m < 0.150\,\mathrm{m\,s^{-1}}} \end{gathered} \tag{3}$$

For the current conditions (property values and cell size), to avoid unrealistic solutions while applying the central differencing scheme, the mean fluid velocity must be considered in the range $0 \leq u_m < 0.15\,\mathrm{m\,s^{-1}}$. Otherwise, non-positive neighboring node coefficients – in particular negative a_{E} coefficients for mean fluid velocities higher that $0.15\,\mathrm{m\,s^{-1}}$ – will be obtained leading to unbounded (unrealistic) solutions.

For the following questions consider the upwind differencing scheme and transient conditions.

(b) (1.5 v.) Considering the mean fluid velocity equal to $0.5\,\mathrm{m\,s^{-1}}$, what should be the maximum time step size (Δt) allowed with the application of the second-order accurate temporal discretization scheme. Present all intermediate calculations.

Solution:

The governing equation can be simplified neglecting the convective term along y (since $v = 0$) and considering the diffusion coefficient $\Gamma = k/c_p$ – see Equation (4).

$$\begin{gathered} \rho c_p \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(\rho u c_p T\right) + \frac{\partial}{\partial y}\left(\rho v c_p T\right) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \Leftrightarrow \\ \Leftrightarrow \rho\frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(\rho u T\right) = \frac{\partial}{\partial x}\left(\Gamma\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma\frac{\partial T}{\partial y}\right) \end{gathered} \tag{4}$$

The spatial and temporal integration over the cell volume (ΔV) and time step size (Δt), respectively, of the previous equation is written as follows – see Equation (5).

$$\begin{gathered} \underbrace{\int_{\Delta V}\int_t^{t+\Delta t} \rho\frac{\partial T}{\partial t}dtdV}_{\mathrm{A}} + \underbrace{\int_t^{t+\Delta t}\int_{\Delta V} \frac{\partial}{\partial x}\left(\rho u T\right)dV dt}_{\mathrm{B}} = \\ \underbrace{\int_t^{t+\Delta t}\int_{\Delta V} \frac{\partial}{\partial x}\left(\Gamma\frac{\partial T}{\partial x}\right)dV dt}_{\mathrm{C}} + \underbrace{\int_t^{t+\Delta t}\int_{\Delta V} \frac{\partial}{\partial y}\left(\Gamma\frac{\partial T}{\partial y}\right)dV dt}_{\mathrm{D}} \end{gathered} \tag{5}$$

The temporal and spatial integration followed by the corresponding discretization of the rate of change term of the governing equation (Term A of Equation (5)) is given by Equation (6).

$$\mathrm{A} \equiv \int_{\Delta V}\int_{t}^{t+\Delta t}\rho\frac{\partial T}{\partial t}dtdV = \int_{y_\mathrm{s}}^{y_\mathrm{n}}\int_{x_\mathrm{w}}^{x_\mathrm{e}}\int_{t}^{t+\Delta t}\rho\frac{\partial T}{\partial t}dtdxdy = \rho\left(T_\mathrm{P}^1 - T_\mathrm{P}^0\right)\Delta x\Delta y \tag{6}$$

The temporal and spatial integration and discretization of the remaining terms are performed as follows – see Equations (7) - (9). The upwind differencing scheme is considered for the convective term (Term B of Equation (5)) while for the diffusive terms (Terms C and D of Equation (5)) the central differencing scheme is considered. The second-order accurate temporal discretization scheme (Crank-Nicolson scheme) is applied for temporal discretization.

$$\begin{aligned}\mathrm{B} \equiv \int_{t}^{t+\Delta t}\int_{\Delta V}\frac{\partial}{\partial x}\left(\rho u T\right)dVdt = \int_{t}^{t+\Delta t}\int_{y_\mathrm{s}}^{y_\mathrm{n}}\int_{x_\mathrm{w}}^{x_\mathrm{e}}\frac{\partial}{\partial x}\left(\rho u T\right)dxdydt = \\ \int_{t}^{t+\Delta t}\left[\left(\rho u T\right)_\mathrm{e} - \left(\rho u T\right)_\mathrm{w}\right]\Delta y dt = \int_{t}^{t+\Delta t}F_x\left(T_\mathrm{P} - T_\mathrm{W}\right)\Delta y dt = \\ F_x\Delta y\Delta t\left(\frac{T_\mathrm{P}^0 + T_\mathrm{P}^1}{2} - \frac{T_\mathrm{W}^0 + T_\mathrm{W}^1}{2}\right)\end{aligned} \tag{7}$$

$$\begin{aligned}\mathrm{C} \equiv \int_{t}^{t+\Delta t}\int_{\Delta V}\frac{\partial}{\partial x}\left(\Gamma\frac{\partial T}{\partial x}\right)dVdt = \int_{t}^{t+\Delta t}\int_{y_\mathrm{s}}^{y_\mathrm{n}}\int_{x_\mathrm{w}}^{x_\mathrm{e}}\frac{\partial}{\partial x}\left(\Gamma\frac{\partial T}{\partial x}\right)dxdydt = \\ \int_{t}^{t+\Delta t}\left[\left(\Gamma\frac{\partial T}{\partial x}\right)_\mathrm{e} - \left(\Gamma\frac{\partial T}{\partial x}\right)_\mathrm{w}\right]\Delta y dt = \int_{t}^{t+\Delta t}\left[D_\mathrm{e}\left(T_\mathrm{E} - T_\mathrm{P}\right) - D_\mathrm{w}\left(T_\mathrm{P} - T_\mathrm{W}\right)\right]\Delta y dt = \\ \left[D_\mathrm{e}\frac{T_\mathrm{E}^0 + T_\mathrm{E}^1}{2} + D_\mathrm{w}\frac{T_\mathrm{W}^0 + T_\mathrm{W}^1}{2} - \left(D_\mathrm{e} + D_\mathrm{w}\right)\frac{T_\mathrm{P}^0 + T_\mathrm{P}^1}{2}\right]\Delta y\Delta t\end{aligned} \tag{8}$$

$$\begin{aligned}\mathrm{D} \equiv \int_{t}^{t+\Delta t}\int_{\Delta V}\frac{\partial}{\partial y}\left(\Gamma\frac{\partial T}{\partial y}\right)dVdt = \int_{t}^{t+\Delta t}\int_{x_\mathrm{w}}^{x_\mathrm{e}}\int_{y_\mathrm{s}}^{y_\mathrm{n}}\frac{\partial}{\partial y}\left(\Gamma\frac{\partial T}{\partial y}\right)dydxdt = \\ \int_{t}^{t+\Delta t}\left[\left(\Gamma\frac{\partial T}{\partial y}\right)_\mathrm{n} - \left(\Gamma\frac{\partial T}{\partial y}\right)_\mathrm{s}\right]\Delta x dt = \int_{t}^{t+\Delta t}\left[D_\mathrm{n}\left(T_\mathrm{N} - T_\mathrm{P}\right) - D_\mathrm{s}\left(T_\mathrm{P} - T_\mathrm{S}\right)\right]\Delta x dt \\ \left[D_\mathrm{n}\frac{T_\mathrm{N}^0 + T_\mathrm{N}^1}{2} + D_\mathrm{s}\frac{T_\mathrm{S}^0 + T_\mathrm{S}^1}{2} - \left(D_\mathrm{n} + D_\mathrm{s}\right)\frac{T_\mathrm{P}^0 + T_\mathrm{P}^1}{2}\right]\Delta x\Delta t\end{aligned} \tag{9}$$

The discretized equation for a generic bulk node is obtained by substituting Equations (6)-(9) in Equation (5) – see Equation (10).

$$
\begin{aligned}
&\int_{\Delta V}\int_t^{t+\Delta t}\rho\frac{\partial T}{\partial t}dtdV+\int_t^{t+\Delta t}\int_{\Delta V}\frac{\partial}{\partial x}\left(\rho uT\right)dV dt=\\
&\int_t^{t+\Delta t}\int_{\Delta V}\frac{\partial}{\partial x}\left(\Gamma\frac{\partial T}{\partial x}\right)dV dt+\int_t^{t+\Delta t}\int_{\Delta V}\frac{\partial}{\partial y}\left(\Gamma\frac{\partial T}{\partial y}\right)dV dt\Leftrightarrow\\
&\frac{\rho\Delta x\Delta y}{\Delta t}\left(T_{\mathrm{P}}^1-T_{\mathrm{P}}^0\right)+F_x\Delta y\left(\frac{T_{\mathrm{P}}^0+T_{\mathrm{P}}^1}{2}-\frac{T_{\mathrm{W}}^0+T_{\mathrm{W}}^1}{2}\right)=\\
&\left[D_{\mathrm{e}}\frac{T_{\mathrm{E}}^0+T_{\mathrm{E}}^1}{2}+D_{\mathrm{w}}\frac{T_{\mathrm{W}}^0+T_{\mathrm{W}}^1}{2}-\left(D_{\mathrm{e}}+D_{\mathrm{w}}\right)\frac{T_{\mathrm{P}}^0+T_{\mathrm{P}}^1}{2}\right]\Delta y+\\
&\left[D_{\mathrm{n}}\frac{T_{\mathrm{N}}^0+T_{\mathrm{N}}^1}{2}+D_{\mathrm{s}}\frac{T_{\mathrm{S}}^0+T_{\mathrm{S}}^1}{2}-\left(D_{\mathrm{n}}+D_{\mathrm{s}}\right)\frac{T_{\mathrm{P}}^0+T_{\mathrm{P}}^1}{2}\right]\Delta x\Leftrightarrow\\
&\underbrace{\left[\frac{\rho\Delta x\Delta y}{\Delta t}+\frac{1}{2}\left(D_{\mathrm{w}}\Delta y+F_x\Delta y+D_{\mathrm{e}}\Delta y+D_{\mathrm{s}}\Delta x+D_{\mathrm{n}}\Delta x\right)\right]}_{a_{\mathrm{P}}}T_{\mathrm{P}}^1=\underbrace{\left(D_{\mathrm{w}}+F_x\right)\Delta y}_{a_{\mathrm{W}}}\frac{T_{\mathrm{W}}^0+T_{\mathrm{W}}^1}{2}+\\
&\underbrace{D_{\mathrm{e}}\Delta y}_{a_{\mathrm{E}}}\frac{T_{\mathrm{E}}^0+T_{\mathrm{E}}^1}{2}+\underbrace{D_{\mathrm{s}}\Delta x}_{a_{\mathrm{S}}}\frac{T_{\mathrm{S}}^0+T_{\mathrm{S}}^1}{2}+\underbrace{D_{\mathrm{n}}\Delta x}_{a_{\mathrm{N}}}\frac{T_{\mathrm{N}}^0+T_{\mathrm{N}}^1}{2}+\\
&\underbrace{\left[\frac{\rho\Delta x\Delta y}{\Delta t}-\frac{1}{2}\left(D_{\mathrm{w}}\Delta y+F_x\Delta y+D_{\mathrm{e}}\Delta y+D_{\mathrm{s}}\Delta x+D_{\mathrm{n}}\Delta x\right)\right]}_{>0\text{ For Physically Realistic Solutions}}T_{\mathrm{P}}^0
\end{aligned}
\tag{10}
$$

The maximum allowed time step size (Δt) is dictated by the coefficient of T_{P}^0 that must be positive in order to obtain physically realistic and bounded solutions – stability criterion. (Note that the remaining coefficients (a_{W}, a_{E}, a_{S}, a_{N}, and a_{P}) are always positive.) Noting that the (axial) velocity profile is not uniform – and consequently, the maximum observed velocity ($u_{\max}$) will dictate Δt – and that a uniform 2D mesh in under consideration ($\Delta x = \Delta y$), the maximum allowed time step size is calculated as shown in Equation (11).

$$
\begin{aligned}
&\frac{\rho\Delta x\Delta y}{\Delta t}-\frac{1}{2}\left[D_{\mathrm{w}}\Delta y+F_x\Delta y+D_{\mathrm{e}}\Delta y+D_{\mathrm{s}}\Delta x+D_{\mathrm{n}}\Delta x\right]>0\Leftrightarrow\\
&\Delta t<\frac{2\rho\Delta x\Delta y}{D_{\mathrm{w}}\Delta y+F_x\Delta y+D_{\mathrm{e}}\Delta y+D_{\mathrm{s}}\Delta x+D_{\mathrm{n}}\Delta x}\Leftrightarrow\Delta t<\frac{2\left(\Delta x\right)^2}{u_{\max}\Delta x+4\frac{k}{\rho c_p}}\Leftrightarrow\\
&\Delta t<\frac{2\left(\Delta x\right)^2}{1.5u_m\Delta x+4\frac{k}{\rho c_p}}\Leftrightarrow\Delta t<\frac{2\times0.001^2}{1.5\times0.5\times0.001+4\times\frac{0.05714}{0.4611\times1098}}\Leftrightarrow\boxed{\Delta t<1.665\,\mathrm{ms}}
\end{aligned}
\tag{11}
$$

(c) (1.5 v.) Considering the fully implicit differencing scheme, determine the discretized equation for the boundary node embraced by the control volume with faces coincident to $x = 0$ and $y = H/2$. Present all intermediate calculations including the final expressions required to compute the center-point and neighboring node coefficients – a_{P} and a_{nb}, respectively – and the constant term b.

Solution:

The discretized equation for the corresponding boundary node is obtained considering Equation (5) with Equations (6), and Equations (12) to (14). The fully implicit discretization scheme is considered for the temporal discretization of convective and diffusive terms in Equations (12) to (14).

$$
\begin{aligned}
\mathrm{B} \equiv \int_t^{t+\Delta t} \int_{\Delta V} \frac{\partial}{\partial x} (\rho u T)\, dV dt = \int_t^{t+\Delta t} \left[(\rho u T)_{\mathrm{e}} - (\rho u T)_{\mathrm{w}} \right] \Delta y dt = \\
\int_t^{t+\Delta t} F_x \left(T_{\mathrm{P}} - T_{\mathrm{in}} \right) \Delta y dt = \\
F_x \Delta y \Delta t \left(T_{\mathrm{P}}^1 - T_{\mathrm{in}} \right)
\end{aligned} \tag{12}
$$

$$
\begin{aligned}
\mathrm{C} \equiv \int_t^{t+\Delta t} \int_{\Delta V} \frac{\partial}{\partial x} \left(\Gamma \frac{\partial T}{\partial x} \right) dV dt = \int_t^{t+\Delta t} \left[\left(\Gamma \frac{\partial T}{\partial x} \right)_{\mathrm{e}} - \left(\Gamma \frac{\partial T}{\partial x} \right)_{\mathrm{w}} \right] \Delta y dt = \\
\int_t^{t+\Delta t} \left[D_{\mathrm{e}} \left(T_{\mathrm{E}} - T_{\mathrm{P}} \right) - 2 D_{\mathrm{in}} \left(T_{\mathrm{P}} - T_{\mathrm{in}} \right) \right] \Delta y dt = \left[D_{\mathrm{e}} T_{\mathrm{E}}^1 + 2 D_{\mathrm{in}} T_{\mathrm{in}} - \left(D_{\mathrm{e}} + 2 D_{\mathrm{in}} \right) T_{\mathrm{P}}^1 \right] \Delta y \Delta t
\end{aligned} \tag{13}
$$

$$
\begin{aligned}
\mathrm{D} \equiv \int_t^{t+\Delta t} \int_{\Delta V} \frac{\partial}{\partial y} \left(\Gamma \frac{\partial T}{\partial y} \right) dV dt = \int_t^{t+\Delta t} \left[\left(\Gamma \frac{\partial T}{\partial y} \right)_{\mathrm{n}} - \left(\Gamma \frac{\partial T}{\partial y} \right)_{\mathrm{s}} \right] \Delta x dt = \\
\int_t^{t+\Delta t} \left[\frac{1}{c_p} \frac{2kh}{h \Delta y + 2k} \left(T_\infty - T_{\mathrm{P}} \right) - D_{\mathrm{s}} \left(T_{\mathrm{P}} - T_{\mathrm{S}} \right) \right] \Delta x dt = \\
\int_t^{t+\Delta t} \left[\frac{U}{c_p} \left(T_\infty - T_{\mathrm{P}} \right) - D_{\mathrm{s}} \left(T_{\mathrm{P}} - T_{\mathrm{S}} \right) \right] \Delta x dt = \left[D_{\mathrm{s}} T_{\mathrm{S}}^1 - \left(D_{\mathrm{s}} + \frac{U}{c_p} \right) T_{\mathrm{P}}^1 + \frac{U}{c_p} T_\infty \right] \Delta x \Delta t
\end{aligned} \tag{14}
$$

Finally, the discretized equation is obtained as shown in Equation (15).

$$
\begin{aligned}
\int_{\Delta V} \int_t^{t+\Delta t} \rho \frac{\partial T}{\partial t} dt dV + \int_t^{t+\Delta t} \int_{\Delta V} \frac{\partial}{\partial x} (\rho u T)\, dV dt = \\
\int_t^{t+\Delta t} \int_{\Delta V} \frac{\partial}{\partial x} \left(\Gamma \frac{\partial T}{\partial x} \right) dV dt + \int_t^{t+\Delta t} \int_{\Delta V} \frac{\partial}{\partial y} \left(\Gamma \frac{\partial T}{\partial y} \right) dV dt \Leftrightarrow \\
\frac{\rho \Delta x \Delta y}{\Delta t} \left(T_{\mathrm{P}}^1 - T_{\mathrm{P}}^0 \right) + F_x \Delta y \left(T_{\mathrm{P}}^1 - T_{\mathrm{in}} \right) = \\
\left[D_{\mathrm{e}} T_{\mathrm{E}}^1 + 2 D_{\mathrm{in}} T_{\mathrm{in}} - \left(D_{\mathrm{e}} + 2 D_{\mathrm{in}} \right) T_{\mathrm{P}}^1 \right] \Delta y + \left[D_{\mathrm{s}} T_{\mathrm{S}}^1 - \left(D_{\mathrm{s}} + \frac{U}{c_p} \right) T_{\mathrm{P}}^1 + \frac{U}{c_p} T_\infty \right] \Delta x \Leftrightarrow \\
\underbrace{\left[\frac{\rho \Delta x \Delta y}{\Delta t} + F_x \Delta y + \left(D_{\mathrm{e}} + 2 D_{\mathrm{in}} \right) \Delta y + \left(D_{\mathrm{s}} + \frac{U}{c_p} \right) \Delta x \right]}_{a_{\mathrm{P}}} T_{\mathrm{P}}^1 = \\
0 T_{\mathrm{W}}^1 + D_{\mathrm{e}} \Delta y T_{\mathrm{E}}^1 + D_{\mathrm{s}} \Delta x T_{\mathrm{S}}^1 + 0 T_{\mathrm{N}}^1 + \underbrace{\frac{\rho \Delta x \Delta y}{\Delta t} T_{\mathrm{P}}^0 + 2 D_{\mathrm{in}} \Delta y T_{\mathrm{in}} + F_x \Delta y T_{\mathrm{in}} + \frac{U}{c_p} \Delta x T_\infty}_{b} \Leftrightarrow \\
\boxed{a_{\mathrm{P}} T_{\mathrm{P}}^1 = \sum_{\mathrm{nb}} a_{\mathrm{nb}} T_{\mathrm{nb}}^1 + b}
\end{aligned} \tag{15}
$$

The following table summarizes the expressions required to compute the coefficients and constant term for the discretized equation in consideration.

a_{W}	a_{E}	a_{S}	a_{N}	a_{P}	a_{P}^0	b
0	$D_{\mathrm{e}} \Delta y$	$D_{\mathrm{s}} \Delta x$	0	$\sum a_{\mathrm{nb}} + a_{\mathrm{P}}^0 - S_{\mathrm{P}}^{\mathrm{T}}$	$\rho \Delta x \Delta y / \Delta t$	$a_{\mathrm{P}}^0 + S_{\mathrm{C}}^{\mathrm{T}}$

S_P^T	S_C^T
$-2D_{in}\Delta y - F_x\Delta y - (U/c_p)\,\Delta x$	$2D_{in}\Delta y T_{in} + F_x\Delta y T_{in} + \frac{U}{c_p}\Delta x T_\infty$

To compute the center-point and neighboring node coefficients and constant term b of the discretized equation the following should be first evaluated: $D_e = D_s = D_{in} = \Gamma/\Delta x = k/(c_p\Delta x)$, $F_x = \rho u\,(y_P \equiv (H - \Delta y)/2)$, $U = 2kh/(h\Delta y + 2k)$, and $\Delta x = \Delta y$. All properties and parameter values are known except the mean fluid velocity – required to compute the convective mass flux (F_x) –, the time step size (Δt), and the node temperature at the previous time instant (T_P^0).