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3. Mechanical Devices & Systems
4. Heat Transfer

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4.3.1	**Convection Fundamentals**	
	4.3.1.1	**Convection mechanism**
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❑ Convection HT coefficient, h:

$$h = \frac{-k\,(\partial T/\partial y)_{y=0}}{(T_s - T_\infty)} \quad \text{… … (3.1)}$$

It is an experimentally determined parameter depending on—

- surface geometry,
- nature of fluid motion
- properties of the fluid: k, ρ, c, μ, &
- bulk fluid velocity: V

❑ For Forced Convection:

$$Nu = f(Re, Pr) \quad \text{… … (3.2)}$$

$$Nu = \frac{hL_c}{k} \qquad Re = \frac{\rho\, V L_c}{\mu}$$

$$Pr = \frac{\mu c_p}{k}$$

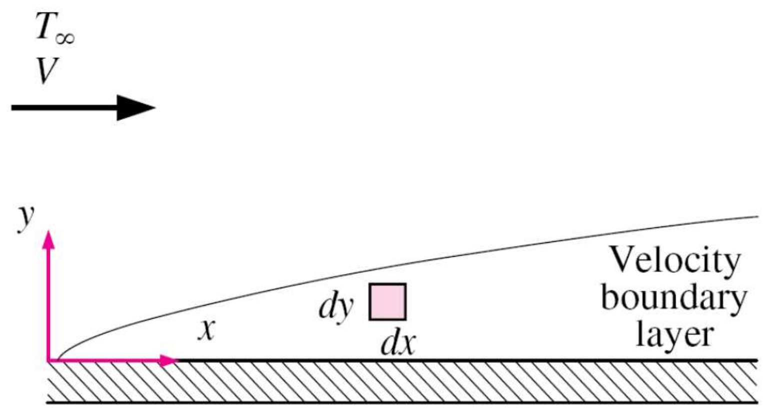
k is the conductivity of fluid

4.3.1.5 Governing Equations for forced convection

- Continuity Equation:
  Conservation of Mass
- Momentum Equation:
  Conservation of Momentum
- Energy Equation:
  Conservation of Energy

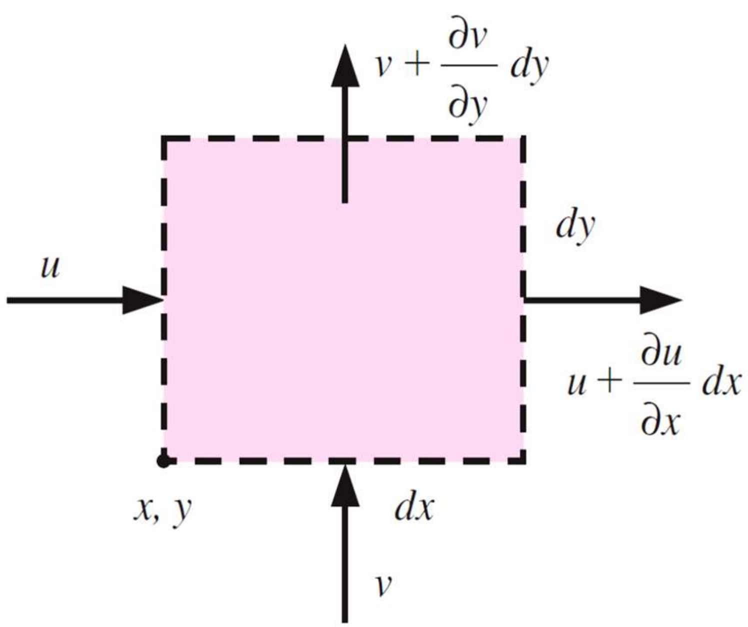
4.3.1.5 Governing Equations for forced convection

❑ Continuity Equation



Assumptions:

- laminar flow over a flat plate
- steady two-dimensional flow
- Newtonian fluid,
- constant properties.

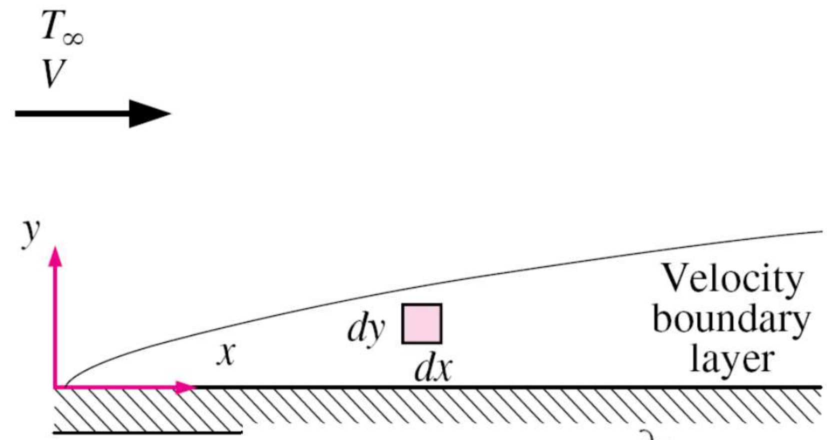


$$\left(\text{Rate of mass flow into the control volume} \right) = \left(\text{Rate of mass flow out of the control volume} \right)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \text{…… (3.11)}$$

4.3.1.5 Governing Equations for forced convection

❑ Momentum Equation

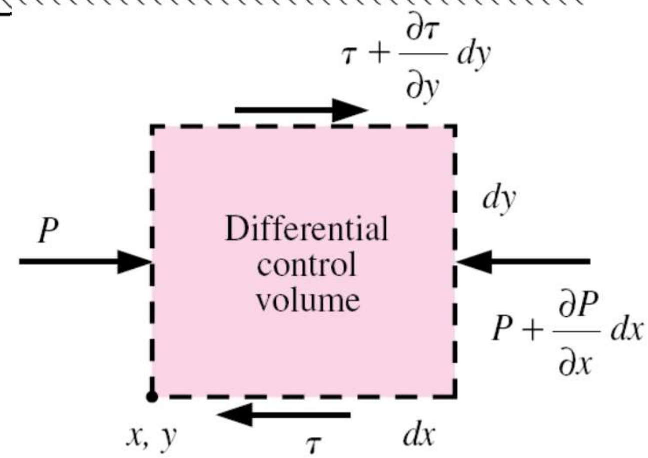


Assumptions:

- laminar flow over a flat plate
- steady two-dimensional flow
- Newtonian fluid,
- constant properties.

Newton's 2nd Law:

$$\sum \mathbf{Force}_x = \text{Rate of change of momentum in x-direction}$$



$$\sum \text{Forces}_x = -\frac{\partial P}{\partial x} dx.dy + \frac{\partial \tau}{\partial y} dx.dy$$

$$\Rightarrow \sum \text{Forces}_x = \left(\mu \frac{\partial^2 u}{\partial y^2} - \frac{\partial P}{\partial x}\right) dx.dy$$

$$\boldsymbol{\tau = \mu \frac{\partial u}{\partial y}}$$

4.3.1.5 Governing Equations for forced convection

Rate of change of momentum in x-direction	=	Mass × Acceleration in x-direction

$$= (\rho\, dx.dy) \times a_x$$

$$= \rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) dx.dy$$

Therefore, (3.12) can be simplified to:

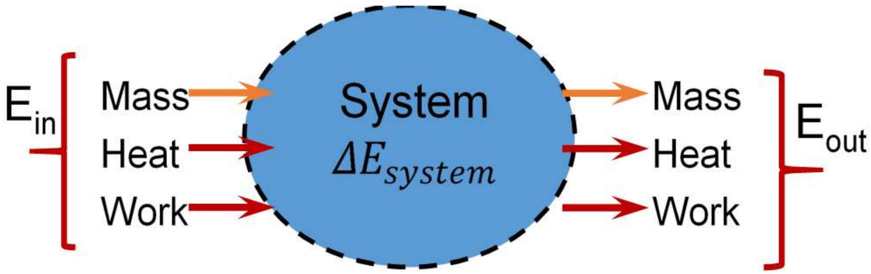
$$\boldsymbol{\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\frac{\partial^2 u}{\partial y^2} - \frac{\partial P}{\partial x}} \dots \dots \textbf{(3.12)}$$

4.3.1.5 Governing Equations for forced convection

❑ Energy Equation

First Law of Thermodynamics:

$$E_{in} - E_{out} = \Delta E_{system}$$



For steady-state conditions with no energy transfer by work, energy balance is given by:

$$\left(\dot{E}_{out} - \dot{E}_{in}\right)_{Heat} + \left(\dot{E}_{out} - \dot{E}_{in}\right)_{Mass} = 0 \qquad \ldots\ldots (3.13)$$

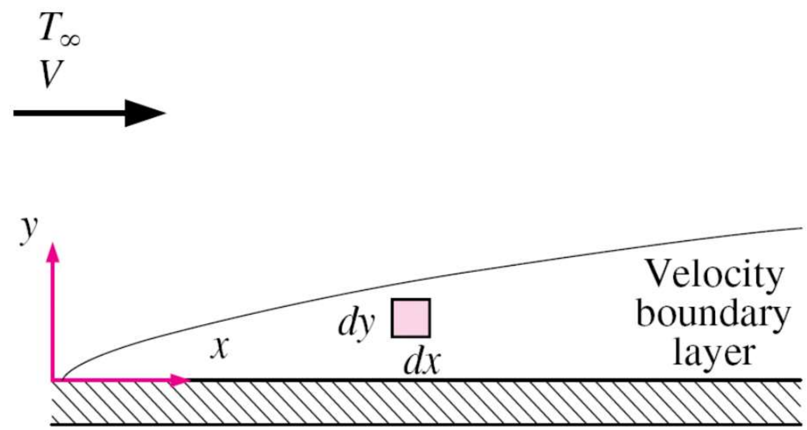
Now, the total rate of Energy of flowing fluid stream is given by:

$$\dot{E} = \dot{m}\,\mathrm{e} = \dot{m}\,(\mathrm{h} + \mathrm{ke} + \mathrm{pe})$$

With negligible kinetic and potential energy, $\dot{E} = \dot{m}\,\mathrm{h} = \dot{m} c_p T$

4.3.1.5 Governing Equations for forced convection

❑ Energy Equation

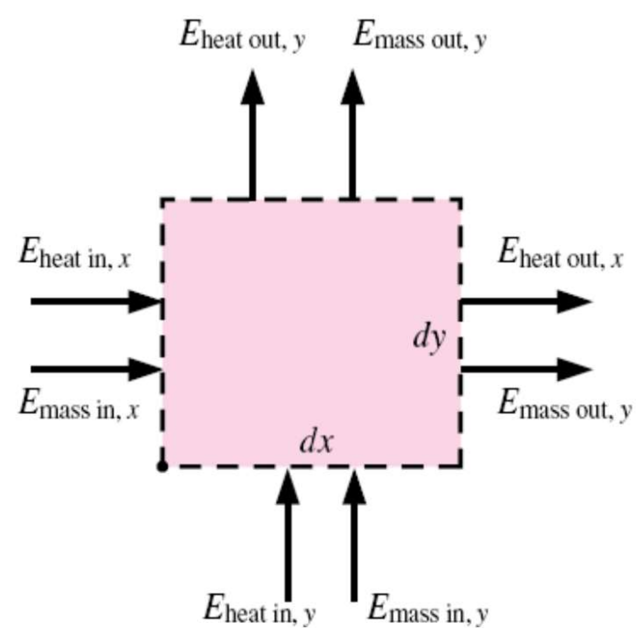


Assumptions

- laminar flow over a flat plate
- steady two-dimensional flow
- Newtonian fluid with constant properties.
- Negligible viscous dissipation

$$\left(\dot{E}_{out} - \dot{E}_{in}\right)_{Mass} = \rho c_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) dxdy$$

$$\left(\dot{E}_{out} - \dot{E}_{in}\right)_{Heat} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) dxdy$$



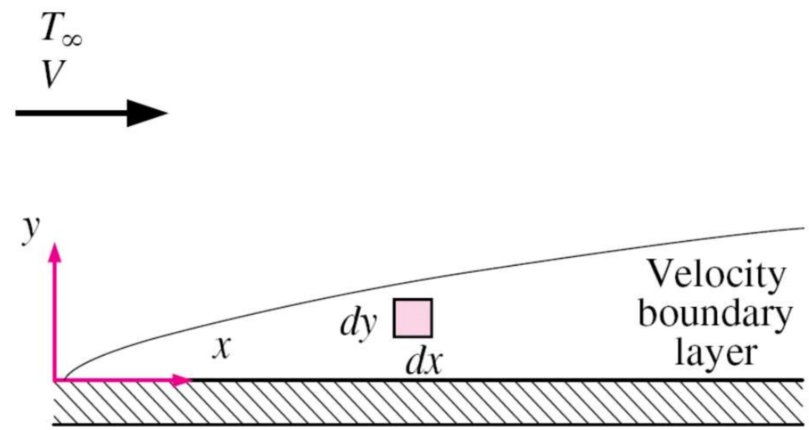
Therefore, Eq. (3.13) can be simplified to:

$$\rho c_p \left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

… … (3.14)

4.3.1.5 Governing Equations for forced convection

❑ Energy Equation



Assumptions

- laminar flow over a flat plate
- steady two-dimensional flow
- Newtonian fluid with constant properties.
- viscous effects are significant

Therefore, (3.13) simplifies to:

$$\rho c_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \mu \Phi \dots \dots \text{(3.15)}$$

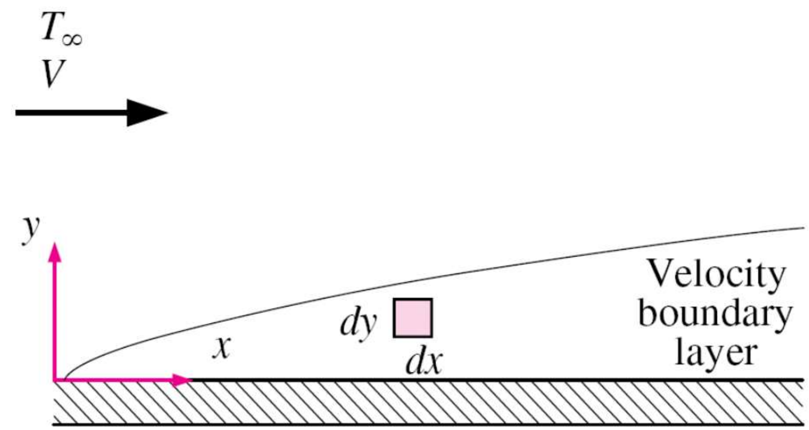
Where,

$$\Phi = 2\left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 \right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2$$

4.3.1.5 Governing Equations for forced convection

Assumptions

- laminar flow over a flat plate
- steady two-dimensional flow
- Newtonian fluid with constant properties.
- viscous effects are significant



$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad \text{…… (3.11)} \quad \textbf{Continuity}$$

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{\partial^2 u}{\partial y^2} - \frac{\partial P}{\partial x} \qquad \text{…… (3.12)} \quad \textbf{Momentum}$$

$$\rho c_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \mu\Phi \qquad \text{…… (3.15)} \quad \textbf{Energy}$$

$$\Phi = 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2$$

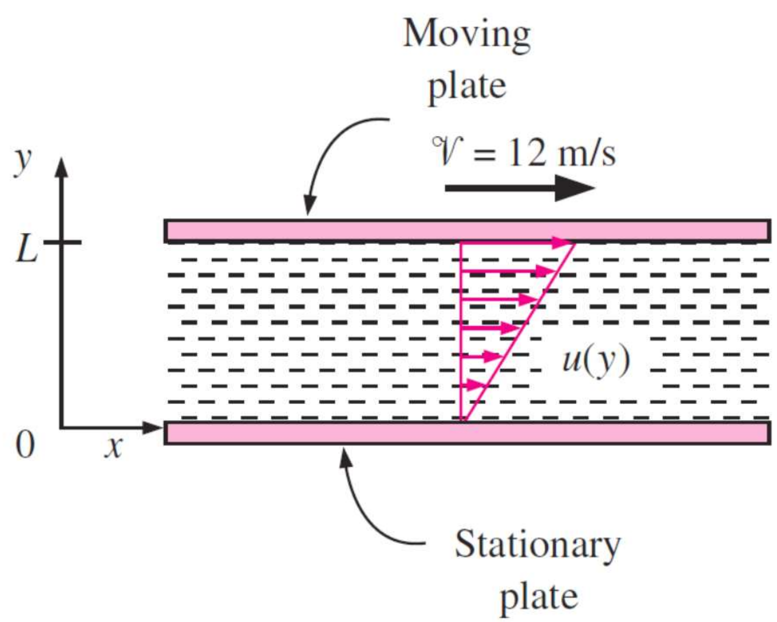
EP# 3.1 Cengel et al. Example: 6-2

The flow of oil in a journal bearing can be approximated as parallel flow between two large plates with one plate moving and the other stationary. Such flows are known as **Couette flow**. Consider two large isothermal plates separated by 2-mm-thick oil film. The upper plates moves at a constant velocity of 12 m/s, while the lower plate is stationary. Both plates are maintained at 20°C.

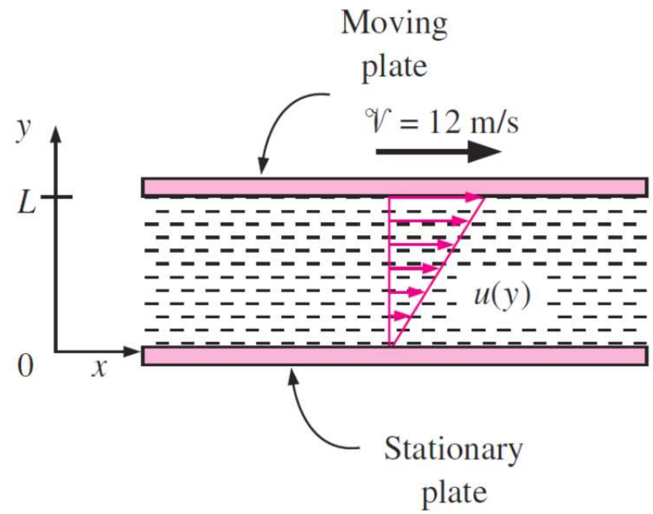
(a) Obtain relations for the velocity and temperature distributions in the oil.

(b) Determine the max temperature in the oil and the heat flux from the oil to each plate.

Oil properties at 20°C:
$k = 0.145$ W/m.K
$\mu = 0.8374$ kg/m.s
$= 0.8374$ N.s/m^2



EP# 3.1 Solution



Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Momentum:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\frac{\partial^2 u}{\partial y^2} - \frac{\partial P}{\partial x}$$

Energy:

$$\rho c_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \mu\Phi$$

$$\Phi = 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2$$