NOTES

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.

2. The examination is an OPEN BOOK EXAM.

3. Candidates may use any non-communicating calculator.

4. Not all problems are of equal weight.

5. Answer all four questions.

6. State all assumptions clearly.
Q1. [50 marks overall] This is a four-part question with each part being of equal weight. In each case you are to start with the appropriate form of the conservation equations [see Tables 1-4 on pp 4-6 taken from Brodkey, R.S. and Hershey H.C. (1988) *Transport Phenomena – A Unified Approach*], make simplifying assumptions and thereby set up the governing differential equation, or equations, that describe the particular problem. **Do not attempt to solve the resulting equations**, however, state appropriate initial and boundary equations and any simplifying assumptions that would be needed to obtain a solution.

(i) Show that the steady-state temperature profile for a fluid flowing under laminar flow within a horizontal cylindrically heated tube is governed by:

\[
\frac{u_{\text{max}}}{1 - \left( \frac{r}{R} \right)^2} \left( \frac{\partial T}{\partial x} \right) = \frac{\alpha}{r} \left( \frac{\partial T}{\partial r} \right)
\]

in which \( u_{\text{max}} \) is the maximum velocity.

(ii) A wall is in contact with a fluid. Suddenly the wall is set in motion as illustrated in Fig. 1. What is the governing differential equation, and the initial and boundary conditions that describe the developing velocity profile?

![Fig. 1: Fluid in contact with a wall](image)

(a) Wall and fluid at rest  (b) Wall moves at velocity \( V \)  (c) Resultant velocity profile

(iii) A Newtonian fluid in a horizontal pipe is initially at rest. Suddenly a pressure drop \( dP/dz \) is imposed on the fluid in the axial direction. What is the governing differential equation, and the initial and boundary conditions that describe the developing velocity profile?

(iv) Transpiration cooling is a process in which fluid is injected through a porous wall whose outer surface is subjected to a severe thermal environment. As the relatively cold fluid passes through the wall, its temperature increases as it absorbs thermal energy: if the flow rate is sufficient, the outer surface of the wall can be maintained at an acceptable temperature. Consider the situation shown in Fig. 2 where the outer surface of a porous wall is subjected to a steady radiative heat flux \( q^* \) [kW/m²]. Fluid is injected through the wall at a rate \( m^* \) [kg/m²·s] from a reservoir (plenum chamber) where the temperature is \( T_0 \). Cooling coils are brazed to the inlet face of the wall, and an additional cooling flux \( q_{\text{eff}}^* \) [kW/m²] can be supplied by passing refrigerant through the coils. If \( k \) is the thermal conductivity of the fluid, and \( k_{\text{eff}} \) is the thermal conductivity of the fluid-solid mixture in the wall, show that the temperature distributions \( T(y) \) in the reservoir and \( T_w(y) \) in the wall are governed by:
\[
\frac{d^2 T}{dy^2} - \frac{\dot{m}^* C_p}{k} \frac{dT}{dy} = 0
\]

and

\[
\frac{d^2 T_w}{dy^2} - \frac{\dot{m}^* C_p}{k_{df}} \frac{dT_w}{dy} = 0
\]

State the bounds for which these equations are valid and stipulate appropriate boundary conditions.

Q2. [15 marks] Two infinite parallel plates are 2-in apart between which is a fluid of viscosity 150 cP. Calculate the shear stress on each plate when the lower plate velocity is 10 ft/min in the positive x-direction and the upper plate velocity is 35 ft/min in the negative x-direction. Also calculate the fluid velocity at \(y\)-in intervals.

Q3. [15 marks] Calculate the heat loss per linear foot from a 3-in sch. 40 steel pipe (3.07-in ID; 3.50-in OD; \(k = 25\) Btu/h ft \(^\circ\)F) covered with \(\Omega\)-in thickness of asbestos insulation (\(k = 0.11\) Btu/h ft \(^\circ\)F). The pipe transports a fluid at 300\(^\circ\)F with an inner convective heat transfer coefficient of 40 Btu/h ft\(^2\) \(^\circ\)F and is exposed to ambient air at 80\(^\circ\)F with and average outer convective heat transfer coefficient of 4.0 Btu/h ft\(^2\) \(^\circ\)F.

Q4. [20 marks] Use Chapman-Enskog theory to calculate the mass diffusivity of the following:

(i) [10 marks] Argon in hydrogen at 1 atm. and 175\(^\circ\)C. The Lennard-Jones parameters for hydrogen are \(\sigma = 2.827 \times 10^{-10}\) m and \((\epsilon/k_B) = 59.7\) K\(^{-1}\); likewise for argon \(\sigma = 3.542 \times 10^{-10}\) m and \((\epsilon/k_B) = 93.3\) K\(^{-1}\). Collision integrals are given in Table 5 on p 7. Comment on your answer in comparison to the experimental value of 1.76 cm\(^2\)/s.

(ii) [10 marks] Argon in zinc vapour at 1037 K and 1 atm. given the molar volume of zinc is 10.19 cm\(^3\)/g-mol and the boiling point is 906\(^\circ\)C.
| Table 1: The Navier-Stokes equations for fluids of constant \( \rho \) and \( \mu \)

Navier–Stokes equation in vector form (rectangular coordinates only)

\[ \frac{\partial U}{\partial t} + (U \cdot \nabla)U = -(1/\rho)\nabla p + \nabla (\nabla^2 U) \]  

(5.15)

Rectangular coordinates

\( x \) component:

\[ \begin{align*}
\frac{\partial U_x}{\partial t} + U_x \frac{\partial U_x}{\partial x} + U_y \frac{\partial U_x}{\partial y} + U_z \frac{\partial U_x}{\partial z} &= -\frac{1}{\rho} \frac{\partial p}{\partial x} + \xi_x + \nu \left( \frac{\partial^2 U_x}{\partial x^2} + \frac{\partial^2 U_x}{\partial y^2} + \frac{\partial^2 U_x}{\partial z^2} \right) \\
&
\end{align*} \]  

(A)

\( y \) component:

\[ \begin{align*}
\frac{\partial U_y}{\partial t} + U_x \frac{\partial U_y}{\partial x} + U_y \frac{\partial U_y}{\partial y} + U_z \frac{\partial U_y}{\partial z} &= -\frac{1}{\rho} \frac{\partial p}{\partial y} + \xi_y + \nu \left( \frac{\partial^2 U_y}{\partial x^2} + \frac{\partial^2 U_y}{\partial y^2} + \frac{\partial^2 U_y}{\partial z^2} \right) \\
&
\end{align*} \]  

(B)

\( z \) component:

\[ \begin{align*}
\frac{\partial U_z}{\partial t} + U_x \frac{\partial U_z}{\partial x} + U_y \frac{\partial U_z}{\partial y} + U_z \frac{\partial U_z}{\partial z} &= -\frac{1}{\rho} \frac{\partial p}{\partial z} + \xi_z + \nu \left( \frac{\partial^2 U_z}{\partial x^2} + \frac{\partial^2 U_z}{\partial y^2} + \frac{\partial^2 U_z}{\partial z^2} \right) \\
&
\end{align*} \]  

(C)

Cylindrical coordinates

\( r \) component:

\[ \begin{align*}
\frac{\partial U_r}{\partial t} + U_r \frac{\partial U_r}{\partial r} + \frac{U_z}{\rho} \frac{\partial U_r}{\partial \theta} + U_\theta \frac{\partial U_r}{\partial \theta} + U_z \frac{\partial U_r}{\partial z} &= -\frac{1}{\rho} \frac{\partial p}{\partial r} + \xi_r + \nu \left( \frac{\partial^2 U_r}{\partial r^2} + \frac{1}{r} \frac{\partial U_r}{\partial \theta} \right) \\
&
\end{align*} \]  

(D)

\( \theta \) component:

\[ \begin{align*}
\frac{\partial U_\theta}{\partial t} + U_r \frac{\partial U_\theta}{\partial r} + U_\theta \frac{\partial U_\theta}{\partial \theta} + \frac{U_z}{\rho} \frac{\partial U_\theta}{\partial \theta} + U_z \frac{\partial U_\theta}{\partial z} &= -\frac{1}{\rho r} \frac{\partial p}{\partial \theta} + \xi_\theta + \nu \left( \frac{\partial^2 U_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial U_\theta}{\partial \theta} \right) \\
&
\end{align*} \]  

(E)

\( z \) component:

\[ \begin{align*}
\frac{\partial U_z}{\partial t} + U_r \frac{\partial U_z}{\partial r} + U_\theta \frac{\partial U_z}{\partial \theta} + \frac{U_z}{\rho} \frac{\partial U_z}{\partial \theta} + U_z \frac{\partial U_z}{\partial z} &= -\frac{1}{\rho} \frac{\partial p}{\partial z} + \xi_z + \nu \left( \frac{\partial^2 U_z}{\partial r^2} + \frac{1}{r} \frac{\partial U_z}{\partial \theta} \right) \\
&
\end{align*} \]  

(F)

Spherical coordinates

\( r \) component:

\[ \begin{align*}
\frac{\partial U_r}{\partial t} + U_r \frac{\partial U_r}{\partial r} + \frac{U_\theta}{r} \frac{\partial U_r}{\partial \theta} + \left( \frac{U_\phi}{r \sin \theta} \right) \frac{\partial U_r}{\partial \phi} + \frac{U_\theta^2}{r^2} \frac{\partial U_r}{\partial \phi} &= -\frac{1}{\rho} \frac{\partial p}{\partial r} + \xi_r + \nu \left( \frac{\partial^2 U_r}{\partial r^2} + \frac{1}{r} \frac{\partial U_r}{\partial \theta} \right) \\
&+ \left( \frac{\nu}{r^2 \sin^2 \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial U_r}{\partial \theta} \right) \right) + \left( \frac{\nu}{r^2 \sin^2 \theta} \frac{\partial^2 U_r}{\partial \phi^2} \right) - \frac{2\nu}{r^2} \frac{\partial U_r}{\partial \phi} \\
&
\end{align*} \]  

(G)

\( \theta \) component:

\[ \begin{align*}
\frac{\partial U_\theta}{\partial t} + U_r \frac{\partial U_\theta}{\partial r} + U_\theta \frac{\partial U_\theta}{\partial \theta} + \left( \frac{U_\phi}{r \sin \theta} \right) \frac{\partial U_\theta}{\partial \phi} + \frac{U_\phi}{r} \frac{\partial U_\theta}{\partial \phi} + \frac{U_\phi^2}{r^2} \frac{\partial U_\theta}{\partial \phi} &= -\frac{1}{\rho r} \frac{\partial p}{\partial \theta} + \xi_\theta + \nu \left( \frac{\partial^2 U_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial U_\theta}{\partial \theta} \right) \\
&+ \left( \frac{\nu}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial U_\theta}{\partial \theta} \right) \right) + \left( \frac{\nu}{r^2 \sin \theta} \frac{\partial^2 U_\theta}{\partial \phi^2} \right) + \left( \frac{2\nu}{r^2 \sin \theta} \frac{\partial U_\theta}{\partial \phi} \right) \\
&
\end{align*} \]  

(H)

\( \phi \) component:

\[ \begin{align*}
\frac{\partial U_\phi}{\partial t} + U_r \frac{\partial U_\phi}{\partial r} + U_\theta \frac{\partial U_\phi}{\partial \theta} + \left( \frac{U_\phi}{r \sin \theta} \right) \frac{\partial U_\phi}{\partial \phi} + \frac{U_\phi}{r} \frac{\partial U_\phi}{\partial \phi} + \frac{U_\phi^2}{r^2} \frac{\partial U_\phi}{\partial \phi} &= -\frac{1}{\rho r \sin \theta} \frac{\partial p}{\partial \phi} + \xi_\phi + \nu \left( \frac{\partial^2 U_\phi}{\partial r^2} + \frac{1}{r} \frac{\partial U_\phi}{\partial \theta} \right) \\
&+ \left( \frac{\nu}{r^2 \sin^2 \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial U_\phi}{\partial \theta} \right) \right) + \left( \frac{2\nu}{r^2 \sin^2 \theta} \frac{\partial^2 U_\phi}{\partial \phi^2} \right) + \left( \frac{2\nu}{r^2 \sin^2 \theta} \frac{\partial U_\phi}{\partial \phi} \right) \\
&
\end{align*} \]  

(I)

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1 Brodkey, R.S. and Hershey H.C. (1988) *Transport Phenomena – A Unified Approach* Table 5.7 p147.
Table 2: Shear stress-velocity gradient relationships for constant viscosity\(^2\)

**Rectangular coordinates**

\[
\begin{align*}
\tau_{xx} &= -2\mu(\partial U_r/\partial x) + (2\mu/3)(\nabla \cdot U) \\
\tau_{yy} &= -2\mu(\partial U_r/\partial y) + (2\mu/3)(\nabla \cdot U) \\
\tau_{zz} &= -2\mu(\partial U_r/\partial z) + (2\mu/3)(\nabla \cdot U) \\
\tau_{xy} &= \tau_{yx} = -\mu[(\partial U_x/\partial y) + (\partial U_y/\partial x)] \\
\tau_{xz} &= \tau_{zx} = -\mu[(\partial U_x/\partial z) + (\partial U_z/\partial x)] \\
\tau_{zx} &= \tau_{xx} = -\mu[(\partial U_x/\partial x) + (\partial U_x/\partial z)] \\

\end{align*}
\]

**Cylindrical coordinates**

\[
\begin{align*}
\tau_{rr} &= -2\mu(\partial U_r/\partial r) + (2\mu/3)(\nabla \cdot U) \\
\tau_{\theta\theta} &= -2\mu \left[ \frac{1}{r} \left( \frac{\partial U_\theta}{\partial \theta} \right) + \frac{U_r}{r} \right] + (2\mu/3)(\nabla \cdot U) \\
\tau_{zz} &= -2\mu(\partial U_z/\partial z) + (2\mu/3)(\nabla \cdot U) \\
\tau_{r\theta} &= \tau_{\theta r} = -\mu \left[ r \frac{\partial}{\partial r} (U_\theta/r) + \frac{1}{r} \left( \frac{\partial U_r}{\partial \theta} \right) \right] \\
\tau_{\theta z} &= \tau_{z\theta} = -\mu \left[ \left( \frac{\partial U_\theta}{\partial z} \right) + \frac{1}{r} \left( \frac{\partial U_z}{\partial \theta} \right) \right] \\
\tau_{rz} &= \tau_{zr} = -\mu[(\partial U_r/\partial z) + (\partial U_z/\partial r)] \\

\end{align*}
\]

**Spherical coordinates**

\[
\begin{align*}
\tau_{rr} &= -2\mu(\partial U_r/\partial r) + (2\mu/3)(\nabla \cdot U) \\
\tau_{\theta\theta} &= -2\mu \left[ \frac{1}{r} \left( \frac{\partial U_\theta}{\partial \theta} \right) + \frac{U_r}{r} \right] + (2\mu/3)(\nabla \cdot U) \\
\tau_{\phi\phi} &= -2\mu \left[ \frac{1}{r \sin \theta} \frac{\partial U_\phi}{\partial \phi} + \frac{U_r}{r} + (U_\theta/r)(\cot \theta) \right] + (2\mu/3)(\nabla \cdot U) \\
\tau_{r\theta} &= \tau_{\theta r} = -\mu \left[ r \frac{\partial}{\partial r} (U_\theta/r) + \frac{1}{r} \left( \frac{\partial U_r}{\partial \theta} \right) \right] \\
\tau_{\theta\phi} &= \tau_{\phi\theta} = -\mu \left[ \sin \theta \left( \frac{\partial}{\partial \theta} \left( \frac{U_\phi}{\sin \theta} \right) \right) + \frac{1}{r \sin \theta} \frac{\partial U_\theta}{\partial \phi} \right] \\
\tau_{\phi r} &= \tau_{r\phi} = -\mu \left[ \frac{1}{r \sin \theta} \frac{\partial U_\phi}{\partial \phi} + r \frac{\partial}{\partial r} (U_\phi/r) \right] \\

\end{align*}
\]

\(^2\) B&H *ibid* Table 5.2 p137.
Table 3: The energy equation

General equation

\[
\frac{\partial (pc_p T)}{\partial t} + (\mathbf{U} \cdot \nabla)(pc_p T) = \dot{I}_A + \nabla \cdot \alpha \nabla (pc_p T) - (pc_p T) (\nabla \cdot \mathbf{U})
\]  
(5.13)

Incompressible media, rectangular coordinates

\[
\frac{\partial T}{\partial t} + U_x \frac{\partial T}{\partial x} + U_y \frac{\partial T}{\partial y} + U_z \frac{\partial T}{\partial z} = \frac{\dot{I}_A}{\rho c_p} + \frac{\partial}{\partial x} \left( \alpha \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \alpha \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \alpha \frac{\partial T}{\partial z} \right)
\]  
(A)

Incompressible media, cylindrical coordinates

\[
\frac{\partial T}{\partial t} + U_r \frac{\partial T}{\partial r} + \frac{U_\theta}{r} \frac{\partial T}{\partial \theta} + U_z \frac{\partial T}{\partial z} = \frac{\dot{I}_A}{\rho c_p} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \alpha \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial \theta} \left( \alpha \frac{\partial T}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( \alpha \frac{\partial T}{\partial z} \right)
\]  
(B)

Incompressible media, spherical coordinates

\[
\frac{\partial T}{\partial t} + U_r \frac{\partial T}{\partial r} + \frac{U_\theta}{r} \frac{\partial T}{\partial \theta} + \frac{U_\phi}{r \sin \theta} \frac{\partial T}{\partial \phi} = \frac{\dot{I}_A}{\rho c_p} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \alpha \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial \theta} \left( \alpha \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \phi} \left( \alpha \frac{\partial T}{\partial \phi} \right)
\]  
(C)

Table 4: The continuity equation for species $A$

General equation

\[
\frac{\partial C_A}{\partial t} + (\mathbf{U} \cdot \nabla)C_A = \dot{C}_{A,\alpha} + (\nabla \cdot D \nabla C_A) - (C_A) (\nabla \cdot \mathbf{U})
\]  
(5.8)

Incompressible media, rectangular coordinates

\[
\frac{\partial C_A}{\partial t} + U_x \frac{\partial C_A}{\partial x} + U_y \frac{\partial C_A}{\partial y} + U_z \frac{\partial C_A}{\partial z} = \dot{C}_{A,\alpha} + \frac{\partial}{\partial x} \left( D \frac{\partial C_A}{\partial x} \right) + \frac{\partial}{\partial y} \left( D \frac{\partial C_A}{\partial y} \right) + \frac{\partial}{\partial z} \left( D \frac{\partial C_A}{\partial z} \right)
\]  
(A)

Incompressible media, cylindrical coordinates

\[
\frac{\partial C_A}{\partial t} + U_r \frac{\partial C_A}{\partial r} + \frac{U_\theta}{r} \frac{\partial C_A}{\partial \theta} + U_z \frac{\partial C_A}{\partial z} = \dot{C}_{A,\alpha} + \frac{1}{r} \frac{\partial}{\partial r} \left( r D \frac{\partial C_A}{\partial r} \right) + \frac{\partial}{\partial \theta} \left( D \frac{\partial C_A}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( D \frac{\partial C_A}{\partial z} \right)
\]  
(B)

Incompressible media, spherical coordinates

\[
\frac{\partial C_A}{\partial t} + U_r \frac{\partial C_A}{\partial r} + \frac{U_\theta}{r} \frac{\partial C_A}{\partial \theta} + \frac{U_\phi}{r \sin \theta} \frac{\partial C_A}{\partial \phi} = \dot{C}_{A,\alpha} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 D \frac{\partial C_A}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( D \frac{\partial C_A}{\partial \theta} \right) + \frac{1}{r^2 \sin \theta \sin \phi} \frac{\partial}{\partial \phi} \left( D \frac{\partial C_A}{\partial \phi} \right)
\]  
(C)

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3 B&H ibid Table 5.6 p143.
4 B&H ibid Table 5.4 p142.
Table 5: Collision Integrals

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<th>( \kappa T/e ) or ( \kappa T/e_{AB} )</th>
<th>( \Omega_\mu = \Omega_\varepsilon ) (For viscosity and thermal conductivity)</th>
<th>( \Omega_{2,AB} ) (For mass diffusivity)</th>
<th>( \kappa T/e ) or ( \kappa T/e_{AB} )</th>
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* Taken from J. O. Hirschfelder, R. B. Bird, and E. L. Spotz, Chem. Revs., 44, 205 (1949).