UNIVERSITY OF JOHANNESBURG

PROGRAM	:	BACCALAUREUS TECHNOLOGIAE *CHEMICAL ENGINEERING*
SUBJECT	:	**CHEMICAL ENGINEERING TECHNOLOGY 4 (HEAT AND MASS)**
CODE	:	**WARC432**
DATE	:	WINTER EXAMINATION 2 JUNE 2014
DURATION	:	(X-PAPER) 08:30 - 11:30
WEIGHT	:	40 : 60
TOTAL MARKS	:	103

EXAMINER	:	DR R. HUBERTS	080207003
MODERATOR	:	PROF M.S. OÑYANGO	2242
NUMBER OF PAGES	:	14	

INSTRUCTIONS	:	ANSWER ALL QUESTIONS. NON-PROGRAMMABLE CALCULATORS PERMITTED (ONLY ONE PER CANDIDATE).

QUESTION 1

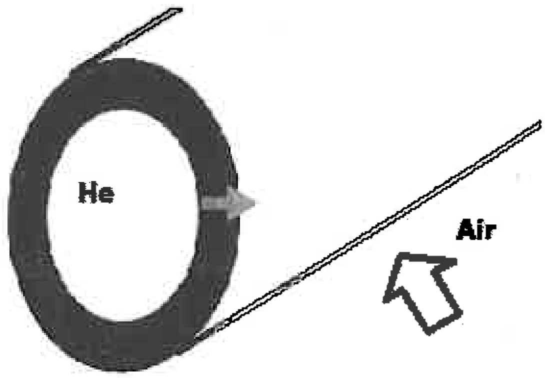
A 2m long black body metal wire of diameter 0.005m and at a temperature of $T_w = 400K$ runs through a grey body hard rubber pipe of outer and inner diameter 0.05m and 0.025m. A vacuum exists between the wire and the inner hard rubber pipe surface. The hard rubber pipe is coated on the outside with a layer of soft rubber, the thickness of which is given on Bb. Draw an annotated diagram of the system. If the temperature of the inner hard rubber area exposed to the vacuum is $T_{si} = 300K$, what is the temperature of the outer soft rubber surface, T_{ho}, at steady state in K? Ignore edge effects and use the thermal conductivity of rubber at 300K.

[33]

QUESTION 2

2.1. Derive the mass diffusion equation (in the radial direction) for steady state one-dimensional diffusion through a stationary cylindrical medium and answer the question on Bb. (4)

Helium gas is transported outside a factory in Durban at 20°C through a silica pipe with outer diameter 0.05m and wall thickness of given on Bb. The absolute pressure in the pipe is maintained at 500kPa.

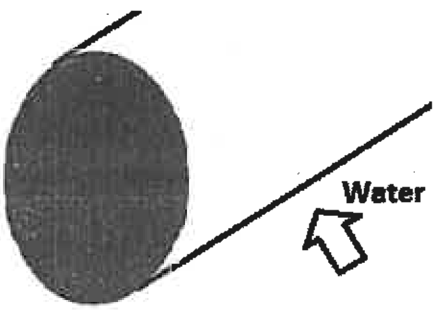


2.2. What is the rate of diffusion of the helium through the silica pipe wall in $mol s^{-1}$ per meter of pipe length? (20)

2.3. If air blows over the pipe at a velocity given on Bb, what is the coefficient, h_m in ms^{-1}, for helium mass transfer from the outer surface of the pipe to the surrounding air? (16)

[40]

QUESTION 3



Boiling water at $0.2ms^{-1}$ flows over a heated cylinder of outer diameter 0.05m.

3.1. What is the heat flux q'' in Wm^{-2} if it is maintained at 80% of the maximum possible? The diameter of the cylinder is given on Bb. Assume a pressure of 1atm. (27)

3.2. Describe the boiling process. (3)

[30]

TOTAL MARKS = 103

FULL MARKS = 103

DATA SHEETS

Lengths, areas and volumes:

Circumference of a circle πd

Area of a cylinder πdL

Area of a circle $\pi d^2/4$

Surface area of a sphere πd^2

Volume of a sphere $\pi d^3/6$

Radiation:

$$F_{21}A_2 = F_{12}A_1$$

Surface Material	Emissivity Coefficient - ε -
Rubber Nat Hard	0.91
Rubber Nat Soft	0.86

TABLE A.3 *Continued*

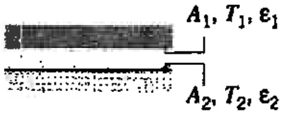
Other Materials (Continued)

Description/ Composition	Temperature (K)	Density, ρ (kg/m³)	Thermal Conductivity, k (W/m · K)	Specific Heat, c_p (J/kg · K)
Ice	273	920	1.88	2040
	253	—	2.03	1945
Leather (sole)	300	998	0.159	—
Paper	300	930	0.180	1340
Paraffin	300	900	0.240	2890
Rock				
Granite, Barre	300	2630	2.79	775
Limestone, Salem	300	2320	2.15	810
Marble, Halston	300	2680	2.80	830
Quartzite, Sioux	300	2640	5.38	1105
Sandstone, Berea	300	2150	2.90	745
Rubber, vulcanized				
Soft	300	1100	0.13	2010
Hard	300	1190	0.16	—
Sand	300	1515	0.27	800
Soil	300	2050	0.52	1840
Snow	273	110	0.049	—
		500	0.190	—
Teflon	300	2200	0.35	—
	400		0.45	—
Tissue, human				
Skin	300	—	0.37	—
Fat layer (adipose)	300	—	0.2	—
Muscle	300	—	0.41	—
Wood, cross grain				
Balsa	300	140	0.055	—
Cypress	300	465	0.097	—
Fir	300	415	0.11	2720
Oak	300	545	0.17	2385
Yellow pine	300	640	0.15	2805
White pine	300	435	0.11	—
Wood, radial				
Oak	300	545	0.19	2385
Fir	300	420	0.14	2720

[a]Adapted from References 1 and 8–13.

TABLE 13.3 Special Diffuse, Gray, Two-Surface Enclosures

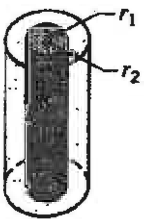
Large (Infinite) Parallel Planes



$$A_1 = A_2 = A \qquad F_{12} = 1$$

$$q_{12} = \frac{A\sigma(T_1^4 - T_2^4)}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1} \tag{13.24}$$

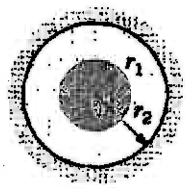
Long (Infinite) Concentric Cylinders



$$\frac{A_1}{A_2} = \frac{r_1}{r_2} \qquad F_{12} = 1$$

$$q_{12} = \frac{\sigma A_1(T_1^4 - T_2^4)}{\dfrac{1}{\varepsilon_1} + \dfrac{1 - \varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1}{r_2}\right)} \tag{13.25}$$

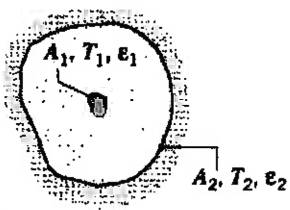
Concentric Spheres



$$\frac{A_1}{A_2} = \frac{r_1^2}{r_2^2} \qquad F_{12} = 1$$

$$q_{12} = \frac{\sigma A_1(T_1^4 - T_2^4)}{\dfrac{1}{\varepsilon_1} + \dfrac{1 - \varepsilon_2}{\varepsilon_2}\left(\dfrac{r_1}{r_2}\right)^2} \tag{13.26}$$

Small Convex Object in a Large Cavity



$$\frac{A_1}{A_2} \approx 0 \qquad F_{12} = 1$$

$$q_{12} = \sigma A_1 \varepsilon_1 (T_1^4 - T_2^4) \tag{13.27}$$

TABLE A.9 Henry's Constant for Selected Gases in Water at Moderate Pressure[a]

$H = p_{A,i}/x_{A,i}$ (bars)

T (K)	NH_3	Cl_2	H_2S	SO_2	CO_2	CH_4	O_2	H_2
273	21	265	260	165	710	22,880	25,500	58,000
280	23	365	335	210	960	27,800	30,500	61,500
290	26	480	450	315	1300	35,200	37,600	66,500
300	30	615	570	440	1730	42,800	45,700	71,600
310	—	755	700	600	2175	50,000	52,500	76,000
320	—	860	835	800	2650	56,300	56,800	78,600
323	—	890	870	850	2870	58,000	58,000	79,000

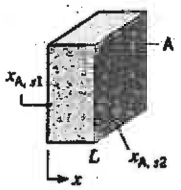
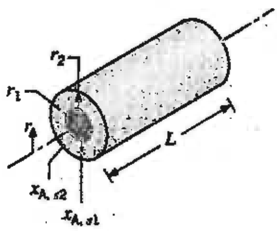
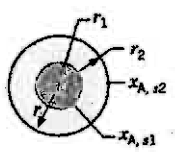
[a]Adapted with permission from Reference 23.

TABLE A.10 The Solubility of Selected Gases and Solids[a]

Gas	Solid	T (K)	$S = C_{A,i}/p_{A,i}$ (kmol/m^3 · bar)
O_2	Rubber	298	3.12×10^{-3}
N_2	Rubber	298	1.56×10^{-3}
CO_2	Rubber	298	40.15×10^{-3}
He	SiO_2	293	0.45×10^{-3}
H_2	Ni	358	9.01×10^{-3}

[a]Adapted with permission from Reference 22.

TABLE 14.1 Summary of Species Diffusion Solutions for Stationary Media with Specified Surface Concentrations[a]

Geometry	Species Concentration Distribution, $x_A(x)$ or $x_A(r)$	Species Diffusion Resistance, $R_{m,\mathrm{dif}}$
	$x_A(x) = (x_{A,s2} - x_{A,s1})\dfrac{x}{L} + x_{A,s1}$	$R_{m,\mathrm{dif}} = \dfrac{L}{D_{AB}A}$ [b]
	$x_A(r) = \dfrac{x_{A,s1} - x_{A,s2}}{\ln(r_1/r_2)} \ln\left(\dfrac{r}{r_2}\right) + x_{A,s2}$	$R_{m,\mathrm{dif}} = \dfrac{\ln(r_2/r_1)}{2\pi L D_{AB}}$ [c]
	$x_A(r) = \dfrac{x_{A,s1} - x_{A,s2}}{1/r_1 - 1/r_2}\left(\dfrac{1}{r} - \dfrac{1}{r_2}\right) + x_{A,s2}$	$R_{m,\mathrm{dif}} = \dfrac{1}{4\pi D_{AB}}\left(\dfrac{1}{r_1} - \dfrac{1}{r_2}\right)$ [c]

[a]Assuming C and D_{AB} are constant.
[b]$N_{A,x} = (C_{A,s1} - C_{A,s2})/R_{m,\mathrm{dif}}$.
[c]$N_{A,r} = (C_{A,s1} - C_{A,s2})/R_{m,\mathrm{dif}}$.

TABLE A.8 Binary Diffusion Coefficients at One Atmosphere[a,b]

Substance A	Substance B	T (K)	D_{AB} (m^2/s)
Gases			
NH_3	Air	298	0.28×10^{-4}
H_2O	Air	298	0.26×10^{-4}
CO_2	Air	298	0.16×10^{-4}
H_2	Air	298	0.41×10^{-4}
O_2	Air	298	0.21×10^{-4}
He	Air	298	0.70×10^{-4}
Acetone	Air	273	0.11×10^{-4}
Benzene	Air	298	0.88×10^{-5}
Naphthalene	Air	300	0.62×10^{-5}
Ar	N_2	293	0.19×10^{-4}
H_2	O_2	273	0.70×10^{-4}
H_2	N_2	273	0.68×10^{-4}
H_2	CO_2	273	0.55×10^{-4}
CO_2	N_2	293	0.16×10^{-4}
CO_2	O_2	273	0.14×10^{-4}
O_2	N_2	273	0.18×10^{-4}
Dilute Solutions			
Caffeine	H_2O	298	0.63×10^{-9}
Ethanol	H_2O	298	0.12×10^{-8}
Glucose	H_2O	298	0.69×10^{-9}
Glycerol	H_2O	298	0.94×10^{-9}
Acetone	H_2O	298	0.13×10^{-8}
CO_2	H_2O	298	0.20×10^{-8}
O_2	H_2O	298	0.24×10^{-8}
H_2	H_2O	298	0.63×10^{-8}
N_2	H_2O	298	0.26×10^{-8}
Solids			
O_2	Rubber	298	0.21×10^{-9}
N_2	Rubber	298	0.15×10^{-9}
CO_2	Rubber	298	0.11×10^{-9}
He	SiO_2	293	0.4×10^{-13}
H_2	Fe	293	0.26×10^{-12}
Cd	Cu	293	0.27×10^{-18}
Al	Cu	293	0.13×10^{-33}

[a] Adapted with permission from References 20, 21, and 22.
[b] Assuming ideal gas behavior, the pressure and temperature dependence of the diffusion coefficient for a binary mixture of gases may be estimated from the relation

$$D_{AB} \propto p^{-1}T^{3/2}$$

TABLE 3.3 One-dimensional, steady-state solutions to the heat equation with no generation

	Plane Wall	Cylindrical Wall[a]	Spherical Wall[a]
Heat equation	$\frac{d^2T}{dx^2} = 0$	$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) = 0$	$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dT}{dr}\right) = 0$
Temperature distribution	$T_{s,1} - \Delta T\frac{x}{L}$	$T_{s,2} + \Delta T\frac{\ln(r/r_2)}{\ln(r_1/r_2)}$	$T_{s,1} - \Delta T\left[\frac{1-(r_1/r)}{1-(r_1/r_2)}\right]$
Heat flux (q'')	$k\frac{\Delta T}{L}$	$\frac{k\Delta T}{r\ln(r_2/r_1)}$	$\frac{k\Delta T}{r^2[(1/r_1)-(1/r_2)]}$
Heat rate (q)	$kA\frac{\Delta T}{L}$	$\frac{2\pi Lk\Delta T}{\ln(r_2/r_1)}$	$\frac{4\pi k\Delta T}{(1/r_1)-(1/r_2)}$
Thermal resistance ($R_{t,cond}$)	$\frac{L}{kA}$	$\frac{\ln(r_2/r_1)}{2\pi Lk}$	$\frac{(1/r_1)-(1/r_2)}{4\pi k}$

[a] The critical radius of insulation is $r_{cr} = k/h$ for the cylinder and $r_{cr} = 2k/h$ for the sphere.

TABLE 8.4 Summary of convection correlations for flow in a circular tube[a,b,e]

Correlation		Conditions
$f = 64/Re_D$	(8.19)	Laminar, fully developed
$Nu_D = 4.36$	(8.53)	Laminar, fully developed, uniform q_s'', $Pr \gtrsim 0.6$
$Nu_D = 3.66$	(8.55)	Laminar, fully developed, uniform T_s, $Pr \gtrsim 0.6$
$\overline{Nu}_D = 3.66 + \frac{0.0668(D/L)Re_D Pr}{1 + 0.04[(D/L)Re_D Pr]^{2/3}}$	(8.56)	Laminar, thermal entry length ($Pr \gg 1$ or an unheated starting length), uniform T_s
or $\overline{Nu}_D = 1.86\left(\frac{Re_D Pr}{L/D}\right)^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14}$	(8.57)	Laminar, combined entry length $\{[Re_D Pr/(L/D)]^{1/3}(\mu/\mu_s)^{0.14}\} \gtrsim 2$, uniform T_s, $0.48 < Pr < 16{,}700$, $0.0044 < (\mu/\mu_s) < 9.75$
$f = 0.316 Re_D^{-1/4}$	(8.20a)[c]	Turbulent, fully developed, $Re_D \lesssim 2 \times 10^4$
$f = 0.184 Re_D^{-1/5}$	(8.20b)[c]	Turbulent, fully developed, $Re_D \gtrsim 2 \times 10^4$
or $f = (0.790 \ln Re_D - 1.64)^{-2}$	(8.21)[c]	Turbulent, fully developed, $3000 \lesssim Re_D \lesssim 5 \times 10^6$
$Nu_D = 0.023 Re_D^{4/5} Pr^n$	(8.60)[d]	Turbulent, fully developed, $0.6 \lesssim Pr \lesssim 160$, $Re_D \gtrsim 10{,}000$, $(L/D) \gtrsim 10$, $n = 0.4$ for $T_s > T_m$ and $n = 0.3$ for $T_s < T_m$
or $Nu_D = 0.027 Re_D^{4/5} Pr^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14}$	(8.61)[d]	Turbulent, fully developed, $0.7 \lesssim Pr \lesssim 16{,}700$, $Re_D \gtrsim 10{,}000$, $L/D \gtrsim 10$
or $Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$	(8.63)[d]	Turbulent, fully developed, $0.5 < Pr < 2000$, $3000 \lesssim Re_D \lesssim 5 \times 10^6$, $(L/D) \gtrsim 10$
$Nu_D = 4.82 + 0.0185(Re_D Pr)^{0.827}$	(8.65)	Liquid metals, turbulent, fully developed, uniform q_s'', $3.6 \times 10^3 < Re_D < 9.05 \times 10^5$, $10^2 < Pe_D < 10^4$
$Nu_D = 5.0 + 0.025(Re_D Pr)^{0.8}$	(8.66)	Liquid metals, turbulent, fully developed, uniform T_s, $Pe_D > 100$

[a]The mass transfer correlations may be obtained by replacing Nu_D and Pr by Sh_D and Sc, respectively.
[b]Properties in Equations 8.53, 8.55, 8.60, 8.61, 8.63, 8.65, and 8.66 are based on T_m; properties in Equations 8.19, 8.20, and 8.21 are based on $T_f \equiv (T_s + T_m)/2$; properties in Equations 8.56 and 8.57 are based on $\overline{T}_m \equiv (T_{m,i} + T_{m,o})/2$.
[c]Equations 8.20 and 8.21 pertain to smooth tubes. For rough tubes, Equation 8.63 should be used with the results of Figure 8.3.
[d]As a first approximation, Equation 8.60, 8.61, or 8.63 may be used to evaluate the average Nusselt number $\overline{Nu}_D$ over the entire tube length, if $(L/D) \gtrsim 10$. The properties should then be evaluated at the average of the mean temperature, $\overline{T}_m \equiv (T_{m,i} + T_{m,o})/2$.
[e]For tubes of noncircular cross section, $Re_D \equiv D_h u_m/\nu$, $D_h \equiv 4A_c/P$, and $u_m = \dot{m}/\rho A_c$. Results for fully developed laminar flow are provided in Table 8.1. For turbulent flow, Equation 8.60 may be used as a first approximation.

TABLE 7.9 Summary of convection heat transfer correlations for external flow[a, b]

Correlation		Geometry	Conditions
$\delta = 5x Re_x^{-1/2}$	(7.19)	Flat plate	Laminar, T_f
$C_{f,x} = 0.664 Re_x^{-1/2}$	(7.20)	Flat plate	Laminar, local, T_f
$Nu_x = 0.332 Re_x^{1/2} Pr^{1/3}$	(7.23)	Flat plate	Laminar, local, T_f, $0.6 \lesssim Pr \lesssim 50$
$\delta_t = \delta Pr^{-1/3}$	(7.24)	Flat plate	Laminar, T_f
$\overline{C}_{f,x} = 1.328 Re_x^{-1/2}$	(7.30)	Flat plate	Laminar, average, T_f
$\overline{Nu}_x = 0.664 Re_x^{1/2} Pr^{1/3}$	(7.31)	Flat plate	Laminar, average, T_f, $0.6 \lesssim Pr \lesssim 50$
$Nu_x = 0.565 Pe_x^{1/2}$	(7.33)	Flat plate	Laminar, local, T_f, $Pr \lesssim 0.05$
$C_{f,x} = 0.0592 Re_x^{-1/5}$	(7.35)	Flat plate	Turbulent, local, T_f, $Re_x \lesssim 10^8$
$\delta = 0.37x Re_x^{-1/5}$	(7.36)	Flat plate	Turbulent, local, T_f, $Re_x \lesssim 10^8$
$Nu_x = 0.0296 Re_x^{4/5} Pr^{1/3}$	(7.37)	Flat plate	Turbulent, local, T_f, $Re_x \lesssim 10^8$, $0.6 \lesssim Pr \lesssim 60$
$\overline{C}_{f,L} = 0.074 Re_L^{-1/5} - 1742 Re_L^{-1}$	(7.43)	Flat plate	Mixed, average, T_f, $Re_{x,c} = 5 \times 10^5$, $Re_L \lesssim 10^8$
$\overline{Nu}_L = (0.037 Re_L^{4/5} - 871) Pr^{1/3}$	(7.41)	Flat plate	Mixed, average, T_f, $Re_{x,c} = 5 \times 10^5$, $Re_L \lesssim 10^8$, $0.6 < Pr < 60$
$\overline{Nu}_D = C Re_D^m Pr^{1/3}$ (Table 7.2)	(7.55b)	Cylinder	Average, T_f, $0.4 < Re_D < 4 \times 10^5$, $Pr \gtrsim 0.7$
$\overline{Nu}_D = C Re_D^m Pr^n (Pr/Pr_s)^{1/4}$ (Table 7.4)	(7.56)	Cylinder	Average, T_∞, $1 < Re_D < 10^6$, $0.7 < Pr < 500$
$\overline{Nu}_D = 0.3 + [0.62 Re_D^{1/2} Pr^{1/3} \times [1 + (0.4/Pr)^{2/3}]^{-1/4}] \times [1 + (Re_D/282{,}000)^{5/8}]^{4/5}$	(7.57)	Cylinder	Average, T_f, $Re_D Pr > 0.2$
$\overline{Nu}_D = 2 + (0.4 Re_D^{1/2} + 0.06 Re_D^{2/3}) Pr^{0.4} \times (\mu/\mu_s)^{1/4}$	(7.59)	Sphere	Average, T_∞, $3.5 < Re_D < 7.6 \times 10^4$, $0.71 < Pr < 380$
$\overline{Nu}_D = 2 + 0.6 Re_D^{1/2} Pr^{1/3}$	(7.60)	Falling drop	Average, T_∞
$\overline{Nu}_D = 1.13 C_1 Re_{D,\max}^m Pr^{1/3}$ (Tables 7.5, 7.6)	(7.63)	Tube bank[c]	Average, $\overline{T}_f$, $2000 < Re_{D,\max} < 4 \times 10^4$, $Pr \gtrsim 0.7$
$\overline{Nu}_D = C Re_{D,\max}^m Pr^{0.36} (Pr/Pr_s)^{1/4}$ (Tables 7.7, 7.8)	(7.67)	Tube bank[c]	Average, $\overline{T}$, $1000 < Re_D < 2 \times 10^6$, $0.7 < Pr < 500$
Single round nozzle	(7.79)	Impinging jet	Average, T_f, $2000 < Re < 4 \times 10^5$, $2 < (H/D) < 12$, $2.5 < (r/D) < 7.5$
Single slot nozzle	(7.82)	Impinging jet	Average, T_f, $3000 < Re < 9 \times 10^4$, $2 < (H/W) < 10$, $4 < (x/W) < 20$
Array of round nozzles	(7.84)	Impinging jet	Average, T_f, $2000 < Re < 10^5$, $2 < (H/D) < 12$, $0.004 < A_r < 0.04$
Array of slot nozzles	(7.87)	Impinging jet	Average, T_f, $1500 < Re < 4 \times 10^4$, $2 < (H/W) < 80$, $0.008 < A_r < 2.5 A_{r,o}$
$\varepsilon \overline{j}_H = \varepsilon \overline{j}_m = 2.06 Re_D^{-0.575}$	(7.91)	Packed bed of spheres[c]	Average, $\overline{T}$, $90 \lesssim Re_D \lesssim 4000$, $Pr \approx 0.7$

[a] Correlations in this table pertain to isothermal surfaces; for special cases involving an unheated starting length or a uniform surface heat flux, see Section 7.2.4.

[b] When the heat and mass transfer analogy is applicable, the corresponding mass transfer correlations may be obtained by replacing Nu and Pr by Sh and Sc, respectively.

[c] For tube banks and packed beds, properties are evaluated at the average fluid temperature, $\overline{T} = (T_i + T_o)/2$, or the average film temperature, $\overline{T}_f = (T_s + \overline{T})/2$.

TABLE 7.2 Constants of Equation 7.55b for the circular cylinder in cross flow [14, 15]

Re_D	C	m
0.4–4	0.989	0.330
4–40	0.911	0.385
40–4000	0.683	0.466
4000–40,000	0.193	0.618
40,000–400,000	0.027	0.805

TABLE A.4 Thermophysical Properties of Gases at Atmospheric Pressure[a]

T (K)	ρ (kg/m³)	c_p (kJ/kg · K)	$\mu \cdot 10^7$ (N · s/m²)	$\nu \cdot 10^6$ (m²/s)	$k \cdot 10^3$ (W/m · K)	$\alpha \cdot 10^6$ (m²/s)	Pr
Air							
100	3.5562	1.032	71.1	2.00	9.34	2.54	0.786
150	2.3364	1.012	103.4	4.426	13.8	5.84	0.758
200	1.7458	1.007	132.5	7.590	18.1	10.3	0.737
250	1.3947	1.006	159.6	11.44	22.3	15.9	0.720
300	1.1614	1.007	184.6	15.89	26.3	22.5	0.707
350	0.9950	1.009	208.2	20.92	30.0	29.9	0.700
400	0.8711	1.014	230.1	26.41	33.8	38.3	0.690
450	0.7740	1.021	250.7	32.39	37.3	47.2	0.686
500	0.6964	1.030	270.1	38.79	40.7	56.7	0.684
550	0.6329	1.040	288.4	45.57	43.9	66.7	0.683
600	0.5804	1.051	305.8	52.69	46.9	76.9	0.685
650	0.5356	1.063	322.5	60.21	49.7	87.3	0.690
700	0.4975	1.075	338.8	68.10	52.4	98.0	0.695
750	0.4643	1.087	354.6	76.37	54.9	109	0.702
800	0.4354	1.099	369.8	84.93	57.3	120	0.709
850	0.4097	1.110	384.3	93.80	59.6	131	0.716
900	0.3868	1.121	398.1	102.9	62.0	143	0.720
950	0.3666	1.131	411.3	112.2	64.3	155	0.723
1000	0.3482	1.141	424.4	121.9	66.7	168	0.726
1100	0.3166	1.159	449.0	141.8	71.5	195	0.728
1200	0.2902	1.175	473.0	162.9	76.3	224	0.728
1300	0.2679	1.189	496.0	185.1	82	238	0.719
1400	0.2488	1.207	530	213	91	303	0.703
1500	0.2322	1.230	557	240	100	350	0.685
1600	0.2177	1.248	584	268	106	390	0.688

TABLE A.6 Thermophysical Properties of Saturated Water[a]

Temperature, T (K)	Pressure, P (bars)[b]	Specific Volume (m^3/kg) $v_f \cdot 10^3$	v_g	Heat of Vaporization, h_{fg} (kJ/kg)	Specific Heat (kJ/kg · K) $c_{p,f}$	$c_{p,g}$	Viscosity (N · s/m²) $\mu_f \cdot 10^6$	$\mu_g \cdot 10^6$	Thermal Conductivity (W/m · K) $k_f \cdot 10^3$	$k_g \cdot 10^3$	Prandtl Number Pr_f	Pr_g	Surface Tension, $\sigma_f \cdot 10^3$ (N/m)	Expansion Coefficient, $\beta_f \cdot 10^6$ (K^{-1})	Temperature, T (K)
273.15	0.00611	1.000	206.3	2502	4.217	1.854	1750	8.02	569	18.2	12.99	0.815	75.5	−68.05	273.15
275	0.00697	1.000	181.7	2497	4.211	1.855	1652	8.09	574	18.3	12.22	0.817	75.3	−32.74	275
280	0.00990	1.000	130.4	2485	4.198	1.858	1422	8.29	582	18.6	10.26	0.825	74.8	46.04	280
285	0.01387	1.000	99.4	2473	4.189	1.861	1225	8.49	590	18.9	8.81	0.833	74.3	114.1	285
290	0.01917	1.001	69.7	2461	4.184	1.864	1080	8.69	598	19.3	7.56	0.841	73.7	174.0	290
295	0.02617	1.002	51.94	2449	4.181	1.868	959	8.89	606	19.5	6.62	0.849	72.7	227.5	295
300	0.03531	1.003	39.13	2438	4.179	1.872	855	9.09	613	19.6	5.83	0.857	71.7	276.1	300
305	0.04712	1.005	29.74	2426	4.178	1.877	769	9.29	620	20.1	5.20	0.865	70.9	320.6	305
310	0.06221	1.007	22.93	2414	4.178	1.882	695	9.49	628	20.4	4.62	0.873	70.0	361.9	310
315	0.08132	1.009	17.82	2402	4.179	1.888	631	9.69	634	20.7	4.16	0.883	69.2	400.4	315
320	0.1053	1.011	13.98	2390	4.180	1.895	577	9.89	640	21.0	3.77	0.894	68.3	436.7	320
325	0.1351	1.013	11.06	2378	4.182	1.903	528	10.09	645	21.3	3.42	0.901	67.5	471.2	325
330	0.1719	1.016	8.82	2366	4.184	1.911	489	10.29	650	21.7	3.15	0.908	66.6	504.0	330
335	0.2167	1.018	7.09	2354	4.186	1.920	453	10.49	656	22.0	2.88	0.916	65.8	535.5	335
340	0.2713	1.021	5.74	2342	4.188	1.930	420	10.69	660	22.3	2.66	0.925	64.9	566.0	340
345	0.3372	1.024	4.683	2329	4.191	1.941	389	10.89	668	22.6	2.45	0.933	64.1	595.4	345
350	0.4163	1.027	3.846	2317	4.195	1.954	365	11.09	668	23.0	2.29	0.942	63.2	624.2	350
355	0.5100	1.030	3.180	2304	4.199	1.968	343	11.29	671	23.3	2.14	0.951	62.3	652.3	355
360	0.6209	1.034	2.645	2291	4.203	1.983	324	11.49	674	23.7	2.02	0.960	61.4	697.9	360
365	0.7514	1.038	2.212	2278	4.209	1.999	306	11.69	677	24.1	1.91	0.969	60.5	707.1	365
370	0.9040	1.041	1.861	2265	4.214	2.017	289	11.89	679	24.5	1.80	0.978	59.5	728.7	370
373.15	1.0133	1.044	1.679	2257	4.217	2.029	279	12.02	680	24.8	1.76	0.984	58.9	750.1	373.15
375	1.0815	1.045	1.574	2252	4.220	2.036	274	12.09	681	24.9	1.70	0.987	58.6	761	375
380	1.2869	1.049	1.337	2239	4.226	2.057	260	12.29	683	25.4	1.61	0.999	57.6	788	380
385	1.5233	1.053	1.142	2225	4.232	2.080	248	12.49	685	25.8	1.53	1.004	56.6	814	385

TABLE 6.2 Selected dimensionless groups of heat and mass transfer

Group	Definition	Interpretation
Biot number (Bi)	$\frac{hL}{k_s}$	Ratio of the internal thermal resistance of a solid to the boundary layer thermal resistance.
Mass transfer Biot number (Bi_m)	$\frac{h_m L}{D_{AB}}$	Ratio of the internal species transfer resistance to the boundary layer species transfer resistance.
Bond number (Bo)	$\frac{g(\rho_l - \rho_v)L^2}{\sigma}$	Ratio of gravitational and surface tension forces.
Coefficient of friction (C_f)	$\frac{\tau_s}{\rho V^2/2}$	Dimensionless surface shear stress.
Eckert number (Ec)	$\frac{V^2}{c_p(T_s - T_\infty)}$	Kinetic energy of the flow relative to the boundary layer enthalpy difference.
Fourier number (Fo)	$\frac{\alpha t}{L^2}$	Ratio of the heat conduction rate to the rate of thermal energy storage in a solid. Dimensionless time.
Mass transfer Fourier number (Fo_m)	$\frac{D_{AB} t}{L^2}$	Ratio of the species diffusion rate to the rate of species storage. Dimensionless time.
Friction factor (f)	$\frac{\Delta p}{(L/D)(\rho u_m^2/2)}$	Dimensionless pressure drop for internal flow.
Grashof number (Gr_L)	$\frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$	Ratio of buoyancy to viscous forces.
Colburn j factor (j_H)	$St\,Pr^{2/3}$	Dimensionless heat transfer coefficient.
Colburn j factor (j_m)	$St_m\,Sc^{2/3}$	Dimensionless mass transfer coefficient.
Jakob number (Ja)	$\frac{c_p(T_s - T_{sat})}{h_{fg}}$	Ratio of sensible to latent energy absorbed during liquid–vapor phase change.
Lewis number (Le)	$\frac{\alpha}{D_{AB}}$	Ratio of the thermal and mass diffusivities.
Nusselt number (Nu_L)	$\frac{hL}{k_f}$	Dimensionless temperature gradient at the surface.
Peclet number (Pe_L)	$\frac{VL}{\alpha} = Re_L Pr$	Dimensionless independent heat transfer parameter.
Prandtl number (Pr)	$\frac{c_p \mu}{k} = \frac{\nu}{\alpha}$	Ratio of the momentum and thermal diffusivities.
Reynolds number (Re_L)	$\frac{VL}{\nu}$	Ratio of the inertia and viscous forces.
Schmidt number (Sc)	$\frac{\nu}{D_{AB}}$	Ratio of the momentum and mass diffusivities.
Sherwood number (Sh_L)	$\frac{h_m L}{D_{AB}}$	Dimensionless concentration gradient at the surface.
Stanton number (St)	$\frac{h}{\rho V c_p} = \frac{Nu_L}{Re_L Pr}$	Modified Nusselt number.
Mass transfer Stanton number (St_m)	$\frac{h_m}{V} = \frac{Sh_L}{Re_L Sc}$	Modified Sherwood number.
Weber number (We)	$\frac{\rho V^2 L}{\sigma}$	Ratio of inertia to surface tension forces.

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Heat transfer at a boiling surface:

$$q_S'' = h(T_S - T_{sat}) = h\Delta T_e \quad .....10.3$$

Nucleate boiling correlation:

$$q_S'' = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f} h_{fg} \Pr_l^n}\right)^3$$

......10.5

Critical heat flux (Kutateladze and Zuber):

$$q''_{\max} = 0.149 h_{fg}\rho_v\left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{1/4} \quad ......10.7$$

TABLE 10.1 Values of $C_{s,f}$ for various surface–fluid combinations [5–7]

Surface–Fluid Combination	$C_{s,f}$	n
Water–copper		
Scored	0.0068	1.0
Polished	0.0130	1.0
Water–stainless steel		
Chemically etched	0.0130	1.0
Mechanically polished	0.0130	1.0
Ground and polished	0.0060	1.0
Water–brass	0.0060	1.0
Water–nickel	0.006	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper		
Polished	0.0154	1.7
Lapped	0.0049	1.7
Benzene–chromium	0.0101	1.7
Ethyl alcohol–chromium	0.0027	1.7

Minimum heat flux (Zuber) (moderate pressures):

$$q''_{\min} = 0.09\rho_v h_{fg}\left[\frac{g\sigma(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4} \quad ......10.8$$

Film pool boiling for Ts<300°C (radiation component low):

$$\overline{Nu}_D = \frac{\overline{h}_{conv}.D}{k_v} = C.\left[\frac{g\sigma(\rho_l - \rho_v)h'_{fg}D^3}{v_v k_v (T_s - T_{sat})}\right]^{1/4} \quad ...10.9$$

C = 0.62 for horizontal cylinders and C = 0.67 for spheres.

$$h'_{fg} = h_{fg} + 0.80c_{p,v}(T_S - T_{sat})$$

Film pool boiling for Ts>300°C:

$$\overline{h}^{4/3} = \overline{h}_{conv}^{4/3} + \overline{h}_{rad}.\overline{h}^{1/3}$$

$$if\ \overline{h}_{rad} \prec \overline{h}_{conv};$$

$$\overline{h} = \overline{h}_{conv} + \frac{3}{4}\overline{h}_{rad} \quad ....10.10$$

$$where\ \overline{h}_{rad} = \frac{\varepsilon\sigma(T_s^4 - T_{sat}^4)}{T_s - T_{sat}}$$

External forced convection boiling of a cylinder in cross flow:...10.12 (High:a Low:b)

High velocity: $\frac{q''_{max}}{\rho_v h_{fg} V} = \frac{1}{\pi}\left[1+\left(\frac{4}{We_D}\right)^{1/3}\right]$

Low velocity: $\frac{q''_{max}}{\rho_v h_{fg} V} = \frac{\left(\rho_l/\rho_v\right)^{3/4}}{169\pi} + \frac{\left(\rho_l/\rho_v\right)^{1/2}}{19.2\pi We_D^{1/3}}$

$$We_D = \frac{\rho V^2 D}{\sigma}$$

If $\frac{q''_{max}}{\rho_v h_{fg} V} \leq \left[\frac{0.275}{\pi}\right]\left[\frac{\rho l}{\rho v}\right]^{1/2} + 1$ **then the velocity is high, otherwise it is low**

CONDENSATION:

Nusselt laminar film condensation correlation:

$$\overline{Nu}_L = \frac{\overline{h}_L.L}{k_L} = 0.943\left[\frac{\rho_L g(\rho_L - \rho_V)h'_{fg}.L^3}{\mu_L.k_L(T_{sat} - T_s)}\right]^{1/4} \quad .....10.31$$

Modified latent heat of formation term for condensation (Rohsenow):

$h'_{fg} = h_{fg}(1+0.68Ja)$ **......10.26**

Total heat transfer to the surface:

$q = \overline{h}_L A(T_{sat} - T_S)$ **.....10.32**

Total condensation rate:

$\dot{m} = \frac{q}{h'_{fg}} = \frac{\overline{h}_L.A.(T_{sat} - T_s)}{h'_{fg}}$ **.....10.33**

Reynolds number for condensation

$\mathrm{Re}_\delta = \frac{4\dot{m}}{\mu_L.b} = \frac{4\rho_l u_m \delta}{\mu_L}$ **.....10.35**

Condensate mass flowrate:

$\dot{m}(x) = \rho_l u_m b\delta(x)$

$\dot{m}(x) = b\frac{g\rho_l(\rho_l - \rho_v)\delta(x)^3}{3\mu_l}$ 10.19

u_m = mean velocity, δ = thickness, b = breadth of plate

Thickness of condensate:

$$\delta(x)=\left[\frac{4k_l\mu_l(T_{sat}-T_S)x}{g\rho_l(\rho_l-\rho_v)h_{fg}}\right]^{1/4}$$

Re$_\delta$ ≤ 30 for wave-free laminar flow:

$$\frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l}=1.47\,\mathrm{Re}_\delta^{-1/3} \quad .....10.37$$

30≤Re$_\delta$ ≤ 1800 for wavy laminar flow:

$$\nu_l=\frac{\mu_l}{\rho_l}$$

$$\frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l}=\frac{\mathrm{Re}_\delta}{1.08\,\mathrm{Re}_\delta^{1.22}-5.2}$$

Re$_\delta$ > 1800 for turbulent flow:

$$\frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l}=\frac{\mathrm{Re}_\delta}{8750+58\,\mathrm{Pr}^{-0.5}(\mathrm{Re}_\delta^{0.75}-253)}$$

TABLE 1.5 Summary of heat transfer processes

Mode	Mechanism(s)	Rate Equation	Equation Number	Transport Property or Coefficient
Conduction	Diffusion of energy due to random molecular motion	$q_x''\ (\mathrm{W/m^2})=-k\frac{dT}{dx}$	(1.1)	k (W/m · K)
Convection	Diffusion of energy due to random molecular motion plus energy transfer due to bulk motion (advection)	$q''\ (\mathrm{W/m^2})=h(T_s-T_\infty)$	(1.3a)	h (W/m^2 · K)
Radiation	Energy transfer by electromagnetic waves	$q''(\mathrm{W/m^2})=\varepsilon\sigma(T_s^4-T_{sur}^4)$ or $q\ (\mathrm{W})=h_rA(T_s-T_{sur})$	(1.7) (1.8)	ε h_r (W/m^2 · K)

TABLE 10.1 Values of $C_{s,f}$ for various surface–fluid combinations [5–7]

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Mechanically polished	0.0130	1.0
Ground and polished	0.0060	1.0
Water–brass	0.0060	1.0
Water–nickel	0.006	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper		
Polished	0.0154	1.7
Lapped	0.0049	1.7
Benzene–chromium	0.0101	1.7
Ethyl alcohol–chromium	0.0027	1.7