UN 0702 POWER PLANT THERMODYNAMICS

QUESTION BANK
ANSWERS TO PROBLEMS

SECTION T THERMODYNAMICS

Steam Cycles and Efficiency

PROBLEM T-12 T-s Diagram

PROBLEM T-13 T-s Diagram

PROBLEM T-15
- $m = 0.308$
- $q_{in} = 1886$ kJ/kg
- $w_{turbine} = 726$ kJ/kg
- $w_{pump} = 5$ kJ/kg
- $\eta = 38.2\%$

PROBLEM T-16
- (a) $n = 0.182$
  - $p = 0.097$
  - $q = 0.081$
  - $\eta = 31.8\%$
- (b) $M = 155$ kg/s
  - $n = 28$ kg/s
  - $p = 15$ kg/s
  - $q = 13$ kg/s

Available Energy

PROBLEM T-21
- (a) $h_1 = 2706.7$ kJ/kg $s_1 = 7.1271$ kJ/kg°K
  - $h_2 = 504.7$ kJ/kg $s_2 = 1.5301$ kJ/kg°K
  - $h_3 = 255.3$ kJ/kg $s_3 = 0.8285$ kJ/kg°K
  - $h_4 = 422.7$ kJ/kg $s_4 = 1.3030$ kJ/kg°K
- (b) $\Omega = 16740$ kJ/s
- (c) $M_{steam} = 7.6$ kg/s
- (d) $\Delta s_{steam} = -5.597$ kJ/kg°K
  - $M_{steam}\,\Delta s_{steam} = -42.54$ kJ/s°K
- (e) $\Delta s_{water} = 0.4745$ kJ/kg°K
  - $M_{water}\Delta s_{water} = 47.45$ kJ/s°K
- (f) $M\Delta s_{total} = 4.91$ kJ/s°K
  - Increase in entropy

PROBLEM T-22
- (a) $h_1 = 3330.3$ kJ/kg $s_1 = 6.9363$ kJ/kg°K
  - $h_2 = 2418.8$ kJ/kg $s_2 = 7.9278$ kJ/kg°K
- (b) $x_2 = 0.941$
  - $m_2 = 0.059$ $m = 5.9\%$
- (c) $\Delta UE = 303.4$ kJ/kg
- (d) $a_1 = 1215.8$ kJ/kg

	(e)	$M = 110$ kg/s	
PROBLEM T-23	(a)	$h_1 = 3249.6$ kJ/kg	$s_1 = 6.2671$ kJ/kg°K
		$h_2 = 3123.2$ kJ/kg	$s_2 = 6.0945$ kJ/kg°K
		$h_3 = 1133.5$ kJ/kg	$s_3 = 2.8459$ kJ/kg°K
	(b)	$M_{water} = 15.88$ kg/s	
	(c)	$EX_{loss} = 2528$ kJ/s	
	(d)	$EX_{loss} = 0.735\%$	
	(e)	$EX_{loss} = 2022$ kW (in electrical output)	

Plant Efficiency

PROBLEM T-31	(b)	(i) $\eta_{cycle} = 43.6\%$
		(ii) $P_{HP\ turbine} = 164.9$ MW
PROBLEM T-32	(a)	(i) $\eta_{cycle} = 43.6\%$
		(ii) $P_{HP\ turbine} = 164.9$ MW
		(iii) BFP = 11.7 MW input (turbine side)
		BFP = 11.8 MW input (water side)
PROBLEM T-33	(b)	(i) PWR: $\Omega_{cw} = 2146$ MJ/s
		$\Omega_{atmosphere} = 42$ MJ/s
		(ii) Coal: $\Omega_{cw} = 1499$ MJ/s
		$\Omega_{atmosphere} = 204$ MJ/s
PROBLEM T-34	(a)	$P_{out} = 666\ 824$ kW
		$\Omega_{in} = 2\ 061\ 738$ kJ/s
		$\eta_{cycle} = 32.3\%$
	(b)	$\eta_{thermal} = 100\%$
		$AE_{in} = 16\ 525$ kJ/s
		$AE_{out} = 14\ 391$ kJ/s
		$\varepsilon = 87\%$
PROBLEM T-35	(a)	$\Omega_{in} = 930\ 000$ kJ/s
		$P_{out} = 430\ 000$ kW
		$\eta_{cycle} = 46.2\%$
	(b)	$M_{in} = 1\ 272\ 912$ kg/hr
		$M_{out} = 1\ 272\ 912$ kg/hr
		$P_{out} = 133$ MW
	(c)	$P_{input} = 8\ 862$ kW
		$P_{actual} = 8741$ kW
	(d)	$P_{input} = 8743$ kW
	(e)	$P_{required} = 7574$ kW
	(f)	$\eta_{pump\ unit} = 85.5\ \%$
		$\eta_{pump\ only} = 86.6\%$

Heat Exchanger Effectiveness

PROBLEM T-42	(a)	$\Omega_{in} = 874\ 500$ kJ/s
		$\Omega_{out} = 854\ 500$ kJ/s

		$\eta_{thermal}$	=	97.7%
		AE_{in}	=	399 300 kJ/s
		AE_{cut}	=	372 200 kJ/s
		ε	=	93.2%
	(b)	Diagram		
	(c)	Diagram		
	(d)	P_{out}	=	249 MW
PROBLEM T-45	(a)	Feedwater: t_{out}	=	190°C
		Drains: t_{out}	=	170°C
	(b)	M_{steam}	=	31.0 kg/s
	(c)	Ω_{total}	=	65.4 kJ/s
	(d)	AE_{in}	=	22 106 kJ/s
		AE_{out}	=	21 750 kJ/kg
		ε	=	98.4%
		Diagram		
PROBLEM T-47		Ω_{in}	=	3 321 000 kJ/s
		Ω_{out}	=	3 261 000 kJ/s
		$\eta_{thermal}$	=	98.2%
		AE_{in}	=	1 606 000 kJ/s
		AE_{out}	=	1 449 000 kJ/s
		ε	=	90.2%
PROBLEM T-48	(a)	Ω_{in}	=	1 394 020 kJ/s
		P_{out}	=	608 068 kW
		η	=	43.6%
	(b)	Ω_{in}	=	65 778 kJ/s
		Ω_{out}	=	65 805 kJ/kg
		η_{cycle}	=	100.0%
		AE_{in}	=	29 699 kJ/s
		AE_{out}	=	29 304 kJ/s
		ε	=	98.7%

Exergy Flow Analysis

PROBLEM T-62	Exergy Flow Diagram
PROBLEM T-63	Exergy Flow Diagram
PROBLEM T-64	Exergy Flow Diagram
PROBLEM T-65	Exergy Flow Diagram

Thermo-economic Analysis

PROBLEM T-71 Refer to Sample Calculation in Notes

SECTION R REACTOR HEAT GENERATION

Reactor Heat Generation

PROBLEM R-41
$N_f = 649 \times 10^{24}$ nuclei/m^3 (approximately using non-rigorous method)
$q^* = 355\ 000$ kW/m^3 (approximate)
$q/A = 727$ kW/m^2 (on outer surface) (approximate)
$N_f = 0.0441 \times 10^{28}$ nuclei/cm^3 (approximately using non-rigorous method)
$q^* = 246$ MW/m^3 (approximately)
$\Omega = 3880$ MW (approximately)

PROBLEM R-42
(a) $t_o = 1133°C$, $t_1 = 446°C$, $t_2 = 338°C$, $t_3 = 304°C$, $t_{water} = 286°C$
(b) Fuel centre (1133°C)
(c) $(q/A)_o = 0$, $(q/A)_1 = 650$ kW/m^2, $(q/A)_2 = 637$ kW/m^2, $(q/A)_3 = 549$ kW/m^2
(d) Fuel surface (650 kW/m^2)
(e) $\Omega = 3880\ MW_{thermal}$

PROBLEM R-43
$N_f = 0.0658 \times 10^{28}$ nuclei/m^3
$q^* = 360$ MW/m^3
$\Omega = 2875$ MW
(a) $t_o = 1056°C$, $t_1 = 517°C$, $t_2 = 394°C$, $t_3 = 364°C$, $t_{water} = 345°C$
(b) Fuel centre (1056°C)
(c) $(q/A)_o = 0$,
$(q/A)_1 = 737$ kW/m^2,
$(q/A)_2 = 722$ kW/m^2
$(q/A)_3 = 635$ kW/m^2
(d) Fuel surface (737 kW/m^2)
(e) $\Omega = 2875\ MW_{thermal}$

PROBLEM R-44
$N_f = 170 \times 10^{24}$ nuclei/m^3
$q^* = 218$ MW/m^3
$\Omega = 2045$ MW
(a) $t_o = 1346°C$, $t_1 = 543°C$, $t_2 = 323°C$, $t_3 = 305°C$, $t_{coolant} = 290°C$
(b) $(q/A)_{rod\ surface} = 606$ kW/m^2
(c) $\Omega = 5.382$ per channel
$\Omega = 2045\ MW_{thermal}$

Reactor Heat Transfer

PROBLEM R-51
Sketch and Explanation

PROBLEM R-52
For $K_{fuel} = 2.5$ W/m°C
$Q = 43.78$ kW
$t_{water} = 285°C$, $t_3 = 302°C$, $t_2 = 358°C$

t_i = 672°C, t_o = 2066°C (maximum)

PROBLEM R-53
$N_{ff} = (N_A/M_{ff})\ r\ f\ \rho\ i$
$N_{ff} = 0.704 \times 10^{21}$ nuclei/cm^3
$V = 10.78 \times 10^6$ cm^3
$\Omega = N_{ff}\ \sigma_f\ \phi\ E_f\ V$
$\Omega = 267\ MW_{thermal}$

Steam Generator and Condenser Heat Transfer

PROBLEM R-61

Primary: p = 15 MPa
t = 304°C
v = 0.001396 m^3/kg
ρ = 716 kg/m^3
$\mu = 90.2 \times 10^{-6}$ kg/ms
k = 0.553 W/m°C
c_p = 5.52 kJ/kg°C
h_{inside} = 37.5 kW/m^2°C

Secondary: p = 5.8 MPa
t = 273°C
$h_{outside} = 2.54\ (\Delta T_x^3)e^{p/1.551}$

At outer surface: $\Omega_{from\ inside} = \Omega_{to\ outside}$

Thus: $(UA\ \Delta T)_{inside} = (h\ A\ \Delta T)_{outside}$

Note: U combines h_{inside} and k_{wall}
k_{wall} = 15 W/m°C
$U_{inside + wall}$ = 8.33 kW/m^2°C

Hence: $T_{wall} = 304 - 0.0128\ (T_{wall} - 273)^4$
Note: Guess T_{wall} and solve by trial and error
$T_{wall} \approx$ 280°C
T_{water} = 273°C
$T_{inside\ wall}$ = 299°C
$T_{coolant}$ = 304°C
$\Omega/A \approx$ 200 kW/m^2

PROBLEM R-62

(a) p = 15 MPa
t = 304°C
v = 0.001396 m^3/kg
ρ = 716 kg/m^3
$\mu = 90.2 \times 10^{-6}$ kg/ms
k = 0.553 W/m°K
c_p = 5.52 kJ/kg°C
V = 6.0 m/s
h_{inside} = 37.5 kW/m^2°C

(b) p = 5.8 MPa
t = 273°C
$h_{outside} = 2.54\ (\Delta T_x^3)e^{p/1.551}$
$h_{outside} = 107\ (T_{wall} - 273)^3$

(c) $A_{surface}$ = 4460 m^2
(d) Estimation to be proven
(e) $(UA\ \Delta T)_{inside}$ = $(hA\ \Delta T)_{outside}$
Note: U combines h_{inside} and k_{wall}
k_{wall} = 15 W/m°C
Note: Guess T_{wall} and solve by trial and error.
t_{wall} ≈ 280°C
$U_{overall}$ = 7.5 kW/m^2°C
Ω = 1000 $MW_{thermal}$
(f) Specified Ω = 928 $MW_{thermal}$

PROBLEM R-63
(a) p_{inlet} = 11.04 MPa, p_{outlet} = 10.04 MPa
t_{inlet} = 267°C t_{outlet} = 312°C
Primary: p = 10 MPa (for evaluation of properties)
t = 290°C (for evaluation of properties)
ρ = 737 kg/m^3
μ = 940 x 10^{-7} kg/ms
k = 593 x 10^{-3} W/m°C
c_p = 5.44 kJ/kg°C
Secondary: p = 4.7 MPa
t = 260°C
(b) Ω = 1862 MJ/s (ignoring boiling)
Ω = 2064 MJ/s (specified)
(c) $A_{surface}$ = 3139 m^3 (calculated)
$A_{surface}$ = 3127 m^3 (specified)
(d) Inside: V = 4.93 m/s
h_{inside} = 36 kW/m^2°C
Ω = 516 MJ/s (for one steam generator)
Ω/A = 164 kW/s (for one steam generator)
ΔT_{inside} = 5°C
ΔT_{tube} = 13°C
$t_{coolant}$ = 290°C
t_1 = 285°C
t_2 = 272°C
t_{water} = 260°C

PROBLEM R-66
(a) Temperature-path length diagram with temperatures as indicated below.
t_{steam} = 30°C
t_{inlet} = 13°C
t_{outlet} = 24°C
$t_{average}$ = 18°C (should be ~19°C)
t_{wall} = 24°C (should be ~25°C)
t_{wall} = 24°C or slightly higher
(should be ρ = 1025 kg/m^3 for sea water)
μ = 0.001056 Ns/m^2 (0.001316 Ns/m^2)
(b) Cooling Water: ρ = 998 kg/m^3

	c_p	=	4.184 kJ/kg°C
	k	=	0.600 W/m°C (0.596 w/m°C)
Condensate:	t	=	30°C (should be ~ 27.5°C)
	ρ	=	996 kg/m^3
	μ	=	0.000797 Ns/m^2 (0.001036 Ns/m^2)
	c_p	=	4.179 kJ/kg°C
	k	=	(0.613 w/m°C)
	h_{fg}	=	2430 kJ/kg

(c) Cooling Water:

R_e	=	34 000 (27 000)
Pr	=	7.36 (9.13)
Nu	=	216
h	=	7200 W/m^2°C (5200 W/m^2°C)

Condensate:

Nu	=	342
h	=	11 124 W/m^2°C (9 000 W/m^2°C)

(d) U = 3979 W/m^2°C (3290 W/m^2°C)

(e) $\theta_{average}$ = 11.5°C
θ_m = 10.6°C

(f) Ω = U A θ_m = 2420 MJ/s (2000 MJ/s)
(2405 MJ/s with steam at 27.5°C)
Ω = M c_p ΔT = 1800 MJ/s

(h) Numbers in brackets are more realistic values. Calculation does not take account of depth of tube bank and build up of condensation films

PROBLEM R-67
(a) Explanation and Sketch
(b) Temperature Profiles
(c) Temperature Profiles

PROBLEM R-68 No solution available

PROBLEM R-69 No solution available

SECTION H REACTOR THERMAL HYDRAULICS

Fuel Channel Conditions

PROBLEM H-51

D_e	=	0.007629 m
L	=	11.15 m
p	=	10 MPa (approximately - for evaluation of properties)
t	=	300°C (approximately - for evaluation of properties)
ρ	=	716 kg/m^3
μ	=	905 x 10^{-7} kg/ms
M	=	26.5 kg/s maximum (22.5 kg/s average)
V	=	10.51 m/s (8.92 m/s)
Re	=	6.36 x 10^5 (5.40 x 10^5)
f	=	0.013
Δh	=	107 m (77 m)
Δp	=	0.752 MPa (0.541 MPa)

$\Delta p_{specified}$ = 0.88 MPa
Calculation ignores: Boiling frictional effect
Spacers in bundles
End effects of channel fittings

PROBLEM H-52
D_e = 0.01178 m
L = 3.658 m
p = 15 MPa
t = 305°C
ρ = 715 kg/m^3
μ = 9.2 x 10^{-5} Ns/m^2
M = 17.64 m^3/s
V = 4.42 m/s
Re = 4.05 x 10^5
f = 0.013
Δp = 30 kPa

PROBLEM H-56
(i) $(t_o - t_l)$ = (400 – 315)
$\Omega_{surface}$ = 47 kW per m length
$(315 - t_2)$ = 10°C
t_2 = 305°C
(ii) $(t_2 - t_w)$ = (305 – 260)
h = 26 kW/m^2°C
(iii) p = 4.7 MPa

PROBLEM H-57
q* = 400 MW/m^3
$\Omega_{surface}$ = 61.58 kW
h = 128 kw/m^2°C
ρ = 762.5 kg/m^3
D_e = 0.008443 m
P_r = 0.870
Re = 65 000 V
Nu = 1876
V = 22 m/s

Two Phase Conditions

PROBLEM H-61
Sketch and explanation

PROBLEM H-62
Assume S = 1
x_e = 0.0364
M = 0.301 kg/s
Ω = 20.3 kW/m

PROBLEM H-63
Assume S = 1
x_e = 0.0712
α_e = 0.753

PROBLEM H-65
Ω_{total} = 5 000 kJ/s
$\Omega_{non\text{-}boiling}$ = 1980 kJ/s
$\Omega_{non\text{-}boiling} / \Omega_{total} = ½ [1 - \cos(\pi H_o / H)]$
H_o = 0.65 m, H_B = 0.85 m

$\Omega_{boiling}$ = 3020 kJ/s
x_e = 0.077
S = 1.8
α_e = 0.532
Re = 3.2×10^5
f = 0.014
$\bar{R}$ = 2.57
$\Delta p_{friction}$ = 11.5 kPa
$\Delta p_{acceleration}$ = 8.3 kPa
Δp_{total} = 19.8 kPa

PROBLEM H-66
$A_{surface}$ = 0.276 m^2
Ω = 261 kW
A_{flow} = 0.00144 m^2
D_e = 0.0226 m
M = 0.624 kg/s
V = 0.6 m/s
S = 2
x_e = 0.290
α_e = 0.776

SECTION W CANDU OPERATIONAL PHENOMENA

Steam Generator Conditions

PROBLEM W-22
(a) Temperature Profile, θ = 20°C, ΔT = 20°C, t_{in} = 310°C
t_{out} = 270°C
(b) Temperature Profile, θ = 20°C, ΔT = 20°C,
t_{sat} = 240°C, p_{sat} = 3.34 MPa

PROBLEM W-23 No solution available
PROBLEM W-24 Explanation
PROBLEM W-25 Explanation
PROBLEM W-26 Explanation
PROBLEM W-27 Explanation
PROBLEM W-28 Explanation
PROBLEM W-29 Explanation

Steam Generator Transients

PROBLEM W-31 Explanation
PROBLEM W-32 Explanation
PROBLEM W-36 Explanation

Steam Generator Level Changes

PROBLEM W-44 Explanation
PROBLEM W-45 Explanation

PROBLEM W-47 Explanation
PROBLEM W-48 Explanation

General Operational Conditions

PROBLEM W-52 $x_e = 2\%$
$\alpha_e = 20\%$
PROBLEM W-53 Sketch
PROBLEM W-54 Sketches and Explanations
PROBLEM W-55 Explanation
PROBLEM W-57 Explanation
PROBLEM W-58
(a) At 0% load: Inventory = 56 000 kg
At 40% load: Inventory = 37 500 kg
At 80% load: Inventory = 31 500 kg
At 0% load: Volume % = 0%
At 40% load: Volume % = 33%
At 80% load: Volume % = 44%
(b) At 40% load and p = 4.8 MPa
$V_{water} = 43.5\ m^3$
$V_{bubbles} = 21.4\ m^3$
(c) At increasing load and p = 4.6 MPa
$V_{water} = 43.5\ m^3$
$V_{bubbles} = 22.4\ m^3$
$\Delta V = 1.0\ m^3$ due to density change
$m_{water} = 34\ 000$ kg
$m_{bubbles} = 5\ 200$ kg
$x_{4.8\ MPa} = 0.153$
(d) Assume isentropic conditions during flashing
$(s_f + x\ s_{fg})_{4.6\ MPa} = (s_f + x\ s_{fg})_{4.8\ MPa}$
$x_{4.6\ MPa} = 0.159$
$m_{bubbles} = 5\ 400$ kg
$V_{bubbles} = 23.2\ m^3$
$\Delta V = 1.8\ m^3$ due to flashing
ΔV total $= 2.8\ m^3$
$D_{stream\ drum} = 4.2$ m
(e) Level Rise = 0.20 m

SECTION D TURBINE DESIGN

Velocity Diagrams

PROBLEM D-12

(a) Plot diagram to scale (1 mm = 10 m/s)

V_{S1} = 1220 m/s
V_{S2} = 884 m/s
V_{S4} = 554 m/s
V_{S5} = 554 m/s
V_{S6} = 244 m/s

(b) P_1 = 49 MW
P_2 = 33 MW
P_3 = 17 MW
P_{total} = 99 MW

PROBLEM D-13

(a) Plot diagram to scale (1 mm - 5 m/s)

V_{S1} = 726 m/s
V_{R1} = 571 m/s
V_{R2} = 517 m/s
V_{S2} = 373 m/s
If θ_2 is assumed to be 20°
V_{S3} = 348 m/s
V_{R3} = 200 m/s
V_{R4} = 181 m/s
V_{S4} = 110 m/s
P = 96 MW
If θ_2 is assumed to be equal to α_1 = 37° answers will be different
V_{S3} = 348 m/s
V_{R3} = 230 m/s
V_{R4} = 208 m/s
V_{S4} = 182 m/s
P = 90 MW

(b) η_{blade} = 77% (for first case)

PROBLEM D-14

(a) $\Delta h_{isentropic}$ = 996 kJ/kg
Δh_{actual} = 867 kJ/kg
V_{S1} = 1317 m/s
V_B = 309 m/s for optimum work
Draw velocity diagram (scale 1 mm = 10 m/s)
V_{R1} = 1032 m/s
V_{R2} = 1001 m/s
V_{S2} = 735 m/s
θ_2 = 25°
V_{S3} = 713 m/s
V_{R3} = 452 m/s

V_{R4} = 438 m/s
V_{S4} = 293 m/s
(b) W_1 = 566 kJ/kg
W_2 = 205 kJ/kg
(c) $\eta_{stage} = w_{total}/\Delta h_{isentropic} = 77.4\%$

PROBLEM D-15
(a) Draw Velocity Diagram
V_{R1} = 231 m/s
V_{R2} = 220 m/s
$\gamma = \phi = 42°$
V_{S2}= 170 m/s
$\delta = 60°$
(b) $P = M (V_{S1} \cos \theta - V_{S2} \cos \delta) V_B$
P = 25 MW
(c) η = 83%

PROBLEM D-16
(a) $\Delta h_{isentropic\ total}$ = 996 kJ/kg
$\Delta h_{isentropic\ each\ stage}$ = 249 kJ/kg
$\Delta h_{actual\ each\ stage}$ = 217 kJ/kg
V_{S1}= 658 m/s (assuming V_{S0} = 0)
$V_B = \frac{1}{2} V_{S1} \cos \theta$ = 309 m/s
Draw First Stage Velocity Diagram
V_{R1}= 388 m/s
$\gamma = \phi = 36°$
V_{R2} = 376 m/s
V_{S2} = 222 m/s
$\delta = 88°$
V_{S3}= 694 m/s (assuming V_{S2} = 222 m/s)
V_B = 309 m/s
Draw Second Stage Velocity Diagram
V_{R3} = 420 m/s
$\gamma = \phi = 35°$
V_{R4} = 407 m/s
V_{S4} = 235 m/s
Third and Fourth Stages similar to Second Stage
$W_{first\ stage}$ = 187 kJ/kg
$W_{second\ stage}$ = 208 kJ/kg
(b) W_{total} = 811 kJ/kg
(c) $\eta_{internal}$ = 81%

Velocity Diagrams

PROBLEM D-21
(a) Sketch of Blading
(b) Δh = 211 kJ/kg
V_{S1}= 650 m/s
$V_B = \frac{1}{2} V_{S1} \cos \theta$ = 305 m/s
Draw Velocity Diagram

V_{R1} = 378 m/s
V_{R2} = 378 m/s
V_{S2} = 222 m/s
(c) θ = 20°
ϕ = 36°
γ = 36°
δ = 90°
(d) W = 187 kJ/kg
(e) η_{blade} = 88%

PROBLEM D-22
(a) Sketch of Blading
(b) Δh_{total} = 134 kJ/kg
Δh_{fixed} = 67 kJ/kg
Δh_{moving} = 67 kJ/kg
$V_{S1} = (2\ \Delta h_{fixed})^{1/2}$ (since V_0 is unknown)
V_{S1} = 366 m/s
$V_B = 0.8\ V_{S1}$ = 293 m/s
Draw Velocity Diagram
γ = 20° (same as θ for 50% reaction)
V_{R1} = 135 m/s
$\Delta h_{moving} = \frac{1}{2} V_{R2}^2 - \frac{1}{2} V_{R1}^2$
V_{R2} = 390 m/s
V_{S2} = 152 m/s
(c) θ = 20°
ϕ = 68°
γ = 20°
δ = 119°
(d) W = 122 kJ/kg
(e) η_{blade} = 91%

PROBLEM D-23
(a) Δh = 996 kJ/kg
V_{S1} = 1411 m/s
V_B = 331 m/s for optimum work
(b) Draw velocity diagram (scale 1 mm = 10 m/s)
(c) θ_1 = 20°
V_{R1} = 1106 m/s
$\gamma_1 = \phi_1$ = 26°
V_{R2} = 1106 m/s
V_{S2} = 821 m/s
θ_2 = 25°
V_{S3} = 821 m/s
V_{R3} = 539 m/s
$\gamma_2 = \phi_2$ = 40°
V_{R4} = 539 m/s
V_{S4} = 356 m/s
(d) w_1 = 658 kJ/kg
w_2 = 274 kJ/kg

(e) $P = 93$ MW

(f) $\eta_{blade} = 94\%$

PROBLEM D-24

(a) $\Delta h_s = 163$ kJ/kg

$\Delta h = 147$ kJ/kg

$\Delta h_{fixed} = 73$ kJ/kg

$\Delta h_{moving} = 73$ kJ/kg

$V_{S0} = 160$ m/s

$\Delta h_{fired} = \frac{1}{2} V_{S1}^2 - \frac{1}{2} V_{S0}^2$

(b) $V_{S1} = 415$ m/s

(c) $V_B = 0.8\ V_{S1} = 332$ m/s

Draw Velocity Diagram

$V_{R1} = 153$ m/s

$\Delta h_{moving} = \frac{1}{2} V_{R2}^2 - \frac{1}{2} V_{R1}^2$

$V_{R2} = 412$ m/s

$V_{S2} = 152$ m/s

$\theta = 20°$

$\phi = 68°$

$\gamma = 20°$ (same as θ)

$\delta = 112°$

(d) $P = \frac{1}{2} M [(V_{S1}^2 - V_{S2}^2) + (V_{V2}^2 - V_{R1}^2)]$

$P = 2220$ kW

PROBLEM D-25

(a) $\Delta h_s = 163$ kJ/kg

$\Delta h_{fixed} = 81$ kJ/kg

$\Delta h_{moving} = 81$ kJ/kg

$h_0 = 2845$ kJ/kg

$h_{1S} = 2764$ kJ/kg (after fixed blades)

$s_0 = 6.886$ kJ/kg°K

$s_{1s} = 6.886$ kJ/kg°K

$p_1 = 0.47$ MPa (between fixed and moving blades)

(b) $\Delta h_s = \eta_{stage}\ \Delta h_s$

$\Delta h_s = 147$ kJ/kg

$\Delta h_{fixed} = 73.5$ kJ/kg

$\Delta h_{moving} = 73.5$ kJ/kg

$V_{s0} = 150$ m/s

$\Delta h_{fixed} = \frac{1}{2} V_{S1}^2 - \frac{1}{2} V_{S0}^2$

$V_{S1} = 412$ m/s

$V_B = 329$ m/s

$V_{R1} = 152$ m/s

(e) $\Delta h_{moving} = \frac{1}{2} V_{R2} - \frac{1}{2} V_{R1}$

$V_{R2} = 412$ m/s

$V_{S2} = 152$ m/s

(d) $P = 587$ kW

PROBLEM D-26

(a) $V_{B\ base} = 144$ m/s

$V_{B\ middle} = 223$ m/s

$V_{B\ tip} = 302$ m/s

V_{S1} = 244 m/s (given)
At mid point $V_B = V_{S1} \cos \theta$ (50% reaction)
θ = 24°
Draw Velocity Diagram at mid point
ϕ = 90°
$V_A = V_{R1}$ = 100 m/s
$V_A = V_{S2}$ = 100 m/s
$\gamma = \theta$ = 24°
V_{R2} = 246 m/s
V_{S2} = 100 m/s
$V_A = V_{S2}$ = 100 m/s
Draw Velocity Diagram at base
ϕ = 50°
$V_A = V_{S1}$ = 100 m/s
γ = 34°
V_{R1} = 126 m/s
V_{R2} = 175 m/s
Draw Velocity Diagram at tip
ϕ = 128°
$V_A = V_{S2}$ = 100 m/s
γ = 18°
V_{R1} = 126 m/s
V_{R2} = 319 m/s
$R = \Delta h_{moving} / \Delta h_{total}$
R_{base} = 27%
R_{tip} = 63%

PROBLEM D-27

Draw a line along the middle of the cross section of the blades from inlet to outlet (parallel to steam flow). Steam should enter and exit smoothly in this direction. Measure the appropriate angles.
$\theta \approx$ 13°
$\phi \approx$ 35°
$\gamma \approx$ 20°
$\delta \approx$ 99°
V_B = 283 m/s
Draw Velocity Diagram to scale.
V_{R1} = 170 m/s
V_{S1} = 434 m/s
V_{S2} = 111 m/s
V_{R2} = 319 m/s
w = 124 kJs
V_A = 110 m/s
v_0 = 0.07341 m^3/kg
A = 0.0707 m^2 (annular steam flow area)
M = 106 kg/s
P = 13 100 kW for 1 stage

P_{total} = 78 900 kW for 6 stages
$\Delta h_{actual} = P_{total}/M$ = 744 kJ/kg
$\Delta h_{isentropic}$ = 875 kJ/kg
Plot expansion on Mollier Chart
$p_{exhaust}$ = 0.045 MPa
$t_{exhaust}$ = 79°C
$m_{exhaust}$ = 7.4%
P = 79 MW

PROBLEM D-27

Consider centre line of fixed and moving blades
Extend centre line beyond tip of blade at both leading and trailing edges
Measure angle between this extended line and line of motion of blades
Estimated angles: $\theta = 13°$
$\phi = 35°$
$\gamma = 20°$
$\delta = 99°$

N = 3600 rev/min
V_B = 283 m/s
$V_{S1} \cos\theta = V_B + V_{R1} \cos\phi$
$V_{S1} \sin\theta = V_{R1} \sin\phi$
Solve for V_{S1} and V_{R1}
V_{S1} = 434 m/s
V_{R1} = 170 m/s
$V_{R2} \cos\gamma = V_B + V_{S2} \cos\alpha$ ($\alpha = 180° - \delta$)
$V_{R2} \sin\gamma = V_{S2} \sin\alpha$ ($\alpha = 180° - \delta$)
Solve for V_{S2} and V_{R2}
V_{S2} = 111 m/s
V_{R2} = 319 m/s
$W = M [V_{S1} \cos\theta - V_{S2} \cos\delta] V_B$
$W = ½ M [(V_{S1}^2 - V_{S2}^2) + (V_{R2}^2 - V_{R1}^2)]$
W = M 124 500 J/kg
$A_{steam\ flow}$ = 0.0707 m^2 (at inlet)
v_0 = 0.07341 m^3/kg
$M = V_a A_{steam\ flow} / v_0$
M = 106 kg/s (based on inlet conditions)
P = 13 000 kW (for one stage)
P = 79 000 kW (for six stages)
Δh = W/M
Δh = 744 kJ/kg
Δh_s = 875 kJ/kg
h_0 = 3124 kJ/kg
S_0 = 6.769 kJ/kg°K
$h_{s\ exhaust}$ = 2339 kJ/kg
$S_{S\ exhaust}$ = 6.769 kJ/kg°K

From Mollier Chart
$p_{exhaust}$ = 0.045 MPa
$h_{exhaust}$ = 2470 kJ/kg
From Mollier Chart
$x_{exhaust}$ = 0.926
$m_{exhaust}$ = 0.074

PROBLEM D-28
(a) Sketch of Blading
(b) N = 1500 rev/min
V_B = 218 m/s
h_0 = 2378 kJ/kg
h_1 = 2254 kJ/kg
V_{S0} = 95 m/s
$\Delta h = \frac{1}{2} V_{S1}^2 - \frac{1}{2} V_{S0}^2$
V_{S1} = 507 m/s
Draw Velocity Diagram
V_{R1} = 311 m/s
V_{R2} = 311 m/s
V_{S2} = 179 m/s
(c) θ = 20°
ϕ = 34°
γ = 34°
δ = 103°
(d) W = 112 kJ/kg
(e) Δh = 124 kJ/kg
KE_{in} = 4 kJ/kg
KE_{out} = 16 kJ/kg
$\Delta h - W$ = 12 kJ/kg
KE_{our} - KE_{in} = 12 kJ/kg

PROBLEM D-29
(a) Sketch of Blading
(b) N = 1500 rev/min
V_B = 410 m/s
h_0 = 2378 kJ/kg
h_2 = 2254 kJ/kg
Δh_{total} = 124 kJ/kg
$\Delta_{h\ fixed}$ = 62 kJ/kg
h_1 = 2316 kJ/kg
$\Delta_{h\ fixed} = \frac{1}{2} V_{S1}^2 - \frac{1}{2} V_{S0}^2$
V_{S1} = 365 m/s
Draw Velocity Diagram
V_{R1} = 142 m/s
$\Delta h_{moving} = \frac{1}{2} V_{R2}^2 - \frac{1}{2} V_{R1}^2$
V_{R2} = 380 m/s
V_{S2} = 140 m/s
(c) θ = 20°
ϕ = 118°

γ = 20°
δ = 68°
(d) W = 119 kJ/kg

Blading Arrangement

PROBLEM D-31 Explanation and Sketches
PROBLEM D-31 Explanation
PROBLEM D-32 Explanation and Sketches
PROBLEM D-32 Identification and Sketches
PROBLEM D-37 Explanation
PROBLEM D-38 Identification and Sketches

SECTION P TURBINE PERFORMANCE

Part Load Operation

PROBLEM P-13 Sketches and Explanation
PROBLEM P-14 (a) h_0 = 3160 kJ/kg (at 3.1 MPa)
h_1 = 3160 kJ/kg (at 2.8 MPa)
S_1 = 6.842 kJ/kg
S_2 = 6.842 kJ/kg
h_2 = 2124 kJ/kg
Δh_S= 1036 kJ/kg
P_{output} = $P_{alternator} + P_{electrical\ loss} + P_{mechanical\ loss}$
P_{output} = 100 000 /0.955 + 1100
P_{output} = 105 800 kW
$\eta_{internal}$ = $P_{output} / M_{steam}\ \Delta h_s$
$\eta_{internal}$ = 0.824
(b) At one half steam flow
M_{steam} = 62 kg/s
p_3 = 1.4 MPa
h_3 = 3160 kJ/kg
S_3 = 7.152 kJ/kg°K
S_4 = 7.152 kJ/kg°K
h_4 = 2221 kJ/kg
Δh_s = 939 kJ/kg
P_{output} = $M_{steam}\ \eta_{internal}\ \Delta h_s$
P_{output} = 48 000 kW
$P_{coupling}$= $P_{output} - P_{loss}$
$P_{coupling}$= 46 900 kW
$P_{generated}$ = $\eta_{electrical}\ P_{coupling}$
$P_{generated}$= 44 800 kW
(c) At one quarter steam flow
M_{steam} = 31 kg/s
p_5 = 0.7 MPa

h_5 = 3160 kJ/kg
S_5 = 7.467 kJ/kg°K
S_6 = 7.467 kJ/kg°K
h_6 = 2319 kJ/kg
Δh_s = 841 kJ/kg
P_{output} = 21 500 kW
$P_{coupling}$ = 20 400 kW
$P_{generator}$ = 19 500 kW

PROBLEM P-17

(a) p_1 = 5 MPa
t_1 = 450°C
h_1 = 3320 kJ/kg
p_2 = 2 MPa
h_2 = 3320 kJ/kg
p_4 = 0.01 mPa
t_4 = 47°C
m_4 = 12%

(b) $\Delta h_{isentropic}$ = 1020 kJ/kg
Δh_{actual} = 857 kJ/kg
h_6 = 2463 kJ/kg

(c) P = 5.1 kw

Steam Sealing Systems

PROBLEM P-21 Sketch and Description
PROBLEM P-22 Sketch and Explanation
PROBLEM P-23 Diagram

Losses and Performance

PROBLEM P-31 Explanation
PROBLEM P-35 Description
PROBLEM P-36 Description and Explanation
PROBLEM P-37 Description and Explanation

Part Load Operation

PROBLEM P-41 Full Load Conditions

M_{steam} = 240 kg/s
h_0 = 3434 kJ/kg (5.0 MPa)
h_1 = 3434 kJ/kg (4.6 MPa)
S_1 = 7.014 kJ/kg°K
S_2 = 7.014 kJ/kg°K
h_2 = 2139 kJ/kg
Δh_s = 1295 kJ/kg
$P_{output} = P_{coupling} + P_{loss}$

P_{output} = 254 MW
P_{output} = $M_{steam}\ \eta_{internal}\ \Delta h_s$
$\eta_{internal}$ = 0.817
Low Load Conditions
M_{steam} = 24 kg/s
h_3 = 3434 kJ/kg (0.46 MPa)
s_3 = 8.059 kJ/kg°K
s_4 = 8.059 kJ/kg°K
h_4 = 2459 kJ/kg
Δh_s = 975 kJ/kg
P_{output} = $M_{steam}\ \eta_{internal}\ \Delta h_2$
P_{output} = 19 MW
$P_{coupling}$ = 15 MW

PROBLEM P-42

(a) h_1 = 2939 kJ/kg
s_1 = 6.8751 kJ/kg°K
s_{2S} = 6.8751 kJ/kg°K
h_{2S} = 2096 kJ/kg
Δh_s = 843 kJ/kg
$\eta_{internal}$ = $\Delta h_a / \Delta h_s$
Δh_a = 691 kJ/kg
h_2 = 2248 kJ/kg
x_2 = 0.87
m_2 = 0.13
t_2 = 33°C

(b) h_3 = 2974 kJ/kg
s_3 = 7.9888 kJ/kg
s_{4S} = 7.9888 kJ/kg
h_{4s} = 2407 kJ/kg
Δh_s = 567 kJ/kg
$\eta_{internal}$ = $\Delta h_a / \Delta h_s$
Δh_a = 397 kJ/kg
h_4 = 2577 kJ/kg
$x_4 > 1$ (superheated)
t_4 = 41°C

PROBLEM P-43

(a) h_1 = 3214 kJ/kg
h_2 = 2064 kJ/kg (isentropic expansion)
h_3 = 2294 kJ/kg (actual expansion)
P = $M_{steam}\ \Delta h_{actual}$
P = 22.1 MW

(b) h_4 = 3214 kJ/kg (throttled to 1 MPa)
h_5 = 2254 kJ/kg (isentropic expansion)
h_6 = 2446 kJ/kg (actual expansion)
P = (1/4) $M_{steam\ max}\ \Delta h_{actual}$
P = 4.6 MW

(c) h_7 = 3214 kJ/kg (throttled to 0.1 MPa)
h_8 = 2580 kJ/kg (isentropic expansion)

h_9 = 2707 kJ/kg (actual expansion)
P = (1/40) $M_{steam\ max}\ \Delta h_{actual}$
P = 0.3 MW

(d) x_3 = 0.889
m_3 = 0.111
t_3 = 33°C
x_6 = 0.952
m_6 = 0.048
t_6 = 33°C
$x_9 > 1$ (superheated)
m_9 = 0
t_9 = 110°C
Diagram

PROBLEM P-45 Explanation

PROBLEM P-48 Sketches

Condenser Operation

PROBLEM P-52 Sketches

PROBLEM P-53 (a) At 30°C: p_{total} = 0.004246 MPa
p_{sat} = 0.004246 MPa
p_{air} = negligible

At 24°C: p_{total} = 0.004246 MPa
p_{sat} = 0.002985 MPa
p_{air} = 0.001261 MPa
$p_{air}\ v_{air} = R_{air}\ T$
v_{air} = 67.62 m^3/kg
v_{steam} = 45.88 m^3/kg (from tables)
Mass of air extracted: m_{air} = 0.0148 kg/m^3
Mass of steam extracted: m_{steam} = 0.0218 kg/m^3
Ratio: m_{air} / m_{steam} = 0.68

(b) Ratio would increase with reducing temperature

PROBLEM P-54 (a) Diagram
(b) Diagram

PROBLEM P-55 (a) Explanation
(b) Explanation
(c) Explanation