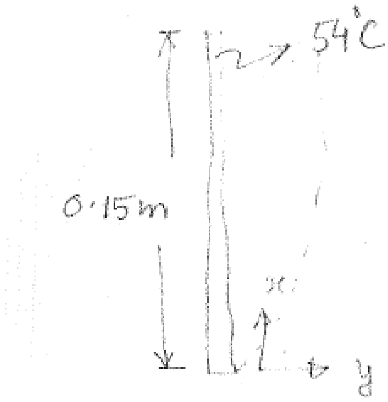
Tutorial-3

Natural convection, Boiling and Condensation

5th-6th Feb 2020

Exercise 1. A number of thin plates are to be cooled by vertically suspending them in a water bath at 20 ^oC. If the plates are initially at 54 ^oC and are 0.15 m long, what minimum spacing would prevent interference between their free convection boundary layers?



Exercise 2. A circular copper pan of 0.3 m diameter is submerged in saturated water. The metal surface temperature is maintained at 118 °C by using electric heater. What should be the power supply to the heater so that the temperature of the plate is maintained? (Pressure = 1 atm)

Exercise 3. The outer surface of a vertical tube is maintained at 50 °C by flow of cooling water through the tube (inside fluid is CW). The tube is 1 m long and has an outer diameter of 80 mm. The tube is exposed to saturated steam at 1 atm. What is the rate of heat transfer to the coolant and what is the rate at which steam is condensed at the surface?

Table 1: External Natural Convection Correlations. Source: Fundamentals of Heat and Mass Transfer, Incropera et al., Seventh Edition

Condition	Correlation
Vertical plate, Laminar flow. Analytical solution of the velocity and thermal boundary layer. Dimensionless velocity profile	Figure 9.4 of Incropera et al. (7th Ed.)
Vertical plate, Laminar flow (Ra $<10^9$), Local Nu. All Pr. Property evaluated at T_f	$$Nu_x = (Gr_x/4)^{1/4} \frac{0.75\sqrt{Pr}}{\left(0.609 + 1.221\sqrt{Pr} + 1.238Pr\right)^{1/4}}$$
Vertical plate, Laminar flow (Ra $<10^9$), Average Nu. All Pr. Property evaluated at T_f	$$\overline{Nu_L} = 4/3 Nu_L$$
Vertical plate, Turbulent flow ($10^9 <$ Ra ¡ 10^{13}). Property evaluated at T_f	$$\overline{Nu} = 0.10 Ra^{1/3}$$
Horizontal cylinder, $Ra_D < 10^{12}$ Property evaluated at T_f.	$$\sqrt{\overline{Nu}} = 0.60 + \frac{0.387 Ra_D^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}$$
Sphere. Property evaluated at T_f. $Ra_D < 10^{11}$; $Pr > 0.7$	$$\overline{Nu} = 2 + \frac{0.589 Ra_D^{1/4}}{[1 + (0.469/Pr)^{9/16}]^{4/9}}$$

Table 2: Correlations for boiling. Source: Fundamentals of Heat and Mass Transfer, Incropera et al., Seventh Edition. Property evaluated at T_{sat}. Refer to the text for various constants such as C_{sf} and n

Condition	Correlation
Nucleate pool boiling (Rohsenow correlation)	$$q'' = \mu_l \lambda \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{\frac{1}{2}} \left(\frac{c_p \Delta T}{C_{sf} \lambda Pr^n}\right)^3$$
Maximum heat flux	$$q''_{max} = C \lambda \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{\frac{1}{4}}$$
Minimum heat flux	$$q''_{min} = C \lambda \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{\frac{1}{4}}$$

Table 3: Heat Transfer Correlations for Condensation on a vertical surface. $Re_\delta \equiv 4\Gamma/\mu_l$. Properties are evaluated at T_f except ρ_v and λ which are evaluated at T_{sat}. The condensate film is always considered to be fully developed.

Condition	**Correlation**
Flat plate. Laminar flow; $Re_\delta < 30$	$$\frac{\overline{h_L}(\nu_l^2/g)^{1/3}}{k_l} = 1.47 Re_\delta^{-1/3}$$ $$Re_\delta = 3.78\left[\frac{k_l L(T_{sat}-T_s)}{(\nu^2/g)^{1/3}\mu_l\lambda}\right]^{3/4}$$
Flat plate. Transition region; $30 < Re_\delta < 1800$	$$\frac{\overline{h_L}(\nu_l^2/g)^{1/3}}{k_l} = \frac{Re_\delta}{1.08 Re_\delta^{1.22} - 5.2}$$ $$Re_\delta = \left[\frac{3.7 k_l L(T_{sat}-T_s)}{(\nu^2/g)^{1/3}\mu_l\lambda}Pr^{0.5} + 4.8\right]^{0.82}$$
Flat plate, Turbulent flow; $Re > 1800$	$$\frac{\overline{h_L}(\nu_l^2/g)^{1/3}}{k_l} = \frac{Re_\delta}{8750 + 58 Pr_l^{-0.5}(Re_\delta^{0.75} - 253)}$$ $$Re_\delta = \left[\frac{0.069 k_l L(T_{sat}-T_s)}{(\nu^2/g)^{1/3}\mu_l\lambda}Pr^{0.5} - 151 Pr^{0.5} + 253\right]^{4/3}$$
Horizontal tube	$$\overline{h_D} = 0.729\left(\frac{g\rho_l(\rho_l-\rho_v)k_l^3\lambda}{\mu_l(T_{sat}-T_s)D}\right)^{1/4}$$

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

Temperature, T (K)	Pressure, p (bars)[b]	Specific Volume (m³/kg) $v \cdot 10^3$	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	664	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