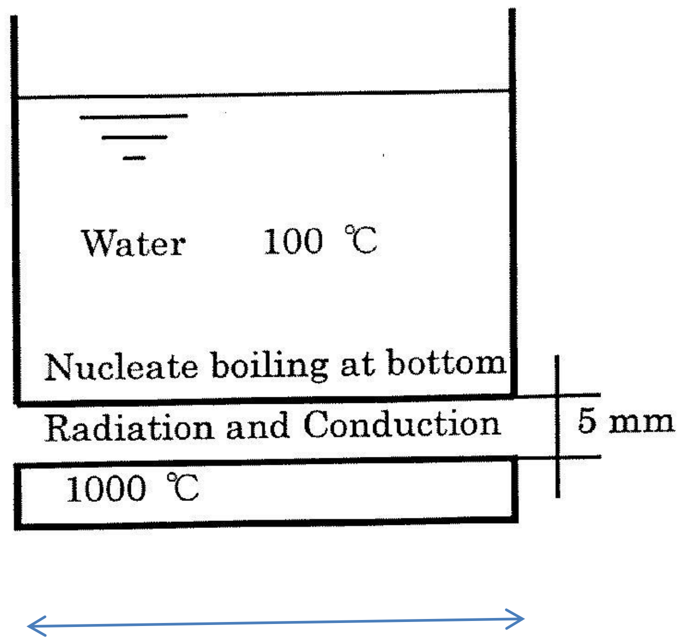
Boiling Heat Transfer Exercise

Exercise 4 – Boiling Heat Transfer

Purpose: Finding temperature under boiling heat transfer condition

Method: Using principles of heat transfer and other relevant correlations (Rohsenow). In this case it is necessary to employ an iterative method to solve the final nonlinear equation.



Pressure = 0.1 MPa

Diameter = 20 cm

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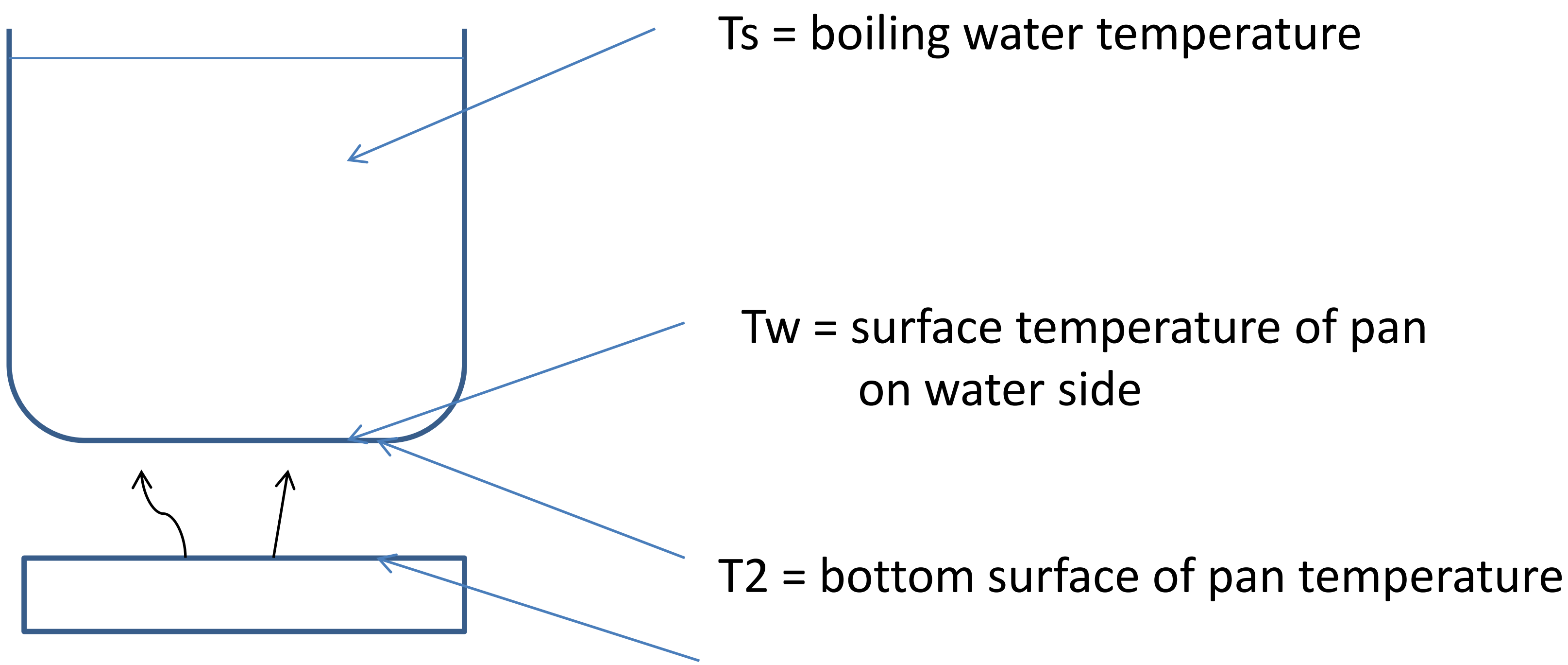
Calculate : The bottom surface temperature of the pan, neglecting resistance of the pan.



$$q = q_{cond} + q_{rad}$$

Between hot plate and pan, both conduction and radiation modes of heat transfer occur in parallel

Exercise 4 – Boiling Heat Transfer

Parameters	
Thermal conductivity of air	$k_a = 0.057\ W/mK$
Specific heat of water	$c_l = 4.215\ kJ/kgK$
Latent heat of water	$h_{fg} = 2256\ kJ/kg$
Prandtl number of water	$Pr = 1.76$
Viscosity of water	$\mu_l = 282.7 \times 10^{-5} Pas$
Surface tension of water	$\sigma = 58.917 \times 10^{-3} N/m$
Gravitational acceleration	$g = 9.807 m/s^2$
Density of liquid water	$\rho_l = 958.0 kg/m^3$
Density of water vapor	$\rho_g = 0.6037 kg/m^3$
Constant= f(liquid, surface material)	$C_{sf} = 0.013$
Stefan-Boltzmann constant	$\sigma = 5.6697 \times 10^{-8} W/m^2K^4$
Emissivity of hot plate	$\varepsilon_1 = 0.7$
Emissivity of bottom surface of pan	$\varepsilon_2 = 0.9$

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T2 = Tw (neglecting resistance of pan), solve for T2

Between hot plate and pan, both conduction and radiation modes of heat transfer occur in parallel

$$q = q_{cond} + q_{rad}$$

For conduction,

$$q_{cond} = -\mathrm{k}\frac{dT}{dx} = -k\frac{(T_1 - T_2)}{\delta}$$

For radiation,

$$q_{rad} = \sigma(T_1^4 - T_2^4)\frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

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For pool nucleate boiling, we can use Rohsenow correlation

$$\frac{c_l(T_2 - T_s)}{h_{fg}} = C_{sf}\left[\frac{q}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}\right]^{0.33} Pr_l^{1.7}$$

Here, q = total q received by pan from conduction and radiation

$$\mathrm{q} = q_{cond} + q_{rad} = -k\frac{(T_1 - T_2)}{\delta} + \sigma(T_1^4 - T_2^4)\frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

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Thus, Rohsenow's correlation becomes

$$\frac{c_l(T_2 - T_s)}{h_{fg}} = C_{sf}\left[\frac{-k\frac{(T_1 - T_2)}{\delta} + \sigma(T_1^4 - T_2^4)\frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}\right]^{0.33} Pr_l^{1.7}$$

<u>This is a nonlinear equation of one variable, T2</u>

- This problem is now a root finding problem with various methods of solving

$$\frac{c_l(T_2 - T_s)}{h_{fg}} - C_{sf}\left[\frac{-k\frac{(T_1 - T_2)}{\delta} + \sigma(T_1^4 - T_2^4)\frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}\right]^{0.33} Pr_l^{1.7} = 0$$

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Using Octave (a free Matlab clone), the built-in function of `fzero` employs the Newton-Raphson method to give the root (=T2) of the equation

We also used the Excel spreadsheet to perform manual iteration to find T2.

Answer,

$T_2 = 386.62\ \mathrm{K} = 113.62\ ^oC$

Corresponding to

Total heat flux of $q'' = 1.0599 \times 10^5 \frac{W}{m^2}$ and

Total heat supplied of $\dot{Q} = 3329.6\ \mathrm{Watts}$

Radiation heat transfer is also larger than conduction in this case,

$q_{cond} = 1.0105 \times 10^4\ Watts$ and $q_{rad} = 9.5881 \times 10^4\ Watts$, almost a whole magnitude larger.

Exercise 4 – Boiling Heat Transfer

Program listing and output

f.m | boill.m | boiling.txt

```
csf = 0.013;
hfg=2256*1000;
cl=4.215*1000;
Pr=1.76;
mu=282.7e-6;
sigma=58.917e-3;
g=9.807;
rhol=958;
rhog=0.6037;
sigmarad=5.6697e-8;
k=0.057;
delta=5e-3;
T1=1273; Ts=373;
epsilon1=0.7; epsilon2=0.9;
diam=0.2;

Area=pi*diam^2/4;

T2=fzero(@f,300)

emissivcoeff=1/((1/epsilon1)+(1/epsilon2)-1);

qrad=sigmarad*(T1^4-T2^4)*emissivcoeff
qcond=k*(T1-T2)/delta

q=k*(T1-T2)/delta+sigmarad*(T1^4-T2^4)*emissivcoeff

Qdot = q*Area
```

Main Program

Exercise 4 – Boiling Heat Transfer

```
function y=f(T2)

csf = 0.013;
hfg=2256*1000;
cl=4.215*1000;
Pr=1.76;
mu=282.7e-6;
sigma=58.917e-3;
g=9.807;
rhol=958;
rhog=0.6037;
sigmarad=5.6697e-8;
k=0.057;
delta=5e-3;
T1=1273; Ts=373;
epsilon1=0.7; epsilon2=0.9;
coeff=sqrt(sigma/(g*(rhol-rhog)))/(mu*hfg);
emissivcoeff=1/((1/epsilon1)+(1/epsilon2)-1);

y=cl*(T2-Ts)/hfg-csf*(Pr^1.7)*((k*(T1-T2)/delta+sigmarad*(T1^4-T2^4)*emissivcoeff)*coeff)^0.33

endfunction
```

Function file to find root for

Exercise 4 – Boiling Heat Transfer

f.m | boill.m | boiling.txt

```
> diary on
octave-3.2.3.exe:9:E:\jaea.course.2015
> boil
y = -0.16196
y = -0.21805
y = -0.10587
y = -0.16383
y = -0.16009
y = -0.44237
y =  0.11852
y = -1.4419e-005
y = -2.0203e-010
y = 4.8572e-017
y = -3.7817e-016
T2 =  386.62
qrad = 9.5881e+004
qcond = 1.0105e+004
q = 1.0599e+005
Qdot =  3329.6
octave-3.2.3.exe:10:E:\jaea.course.2015
> diary off
```

Output

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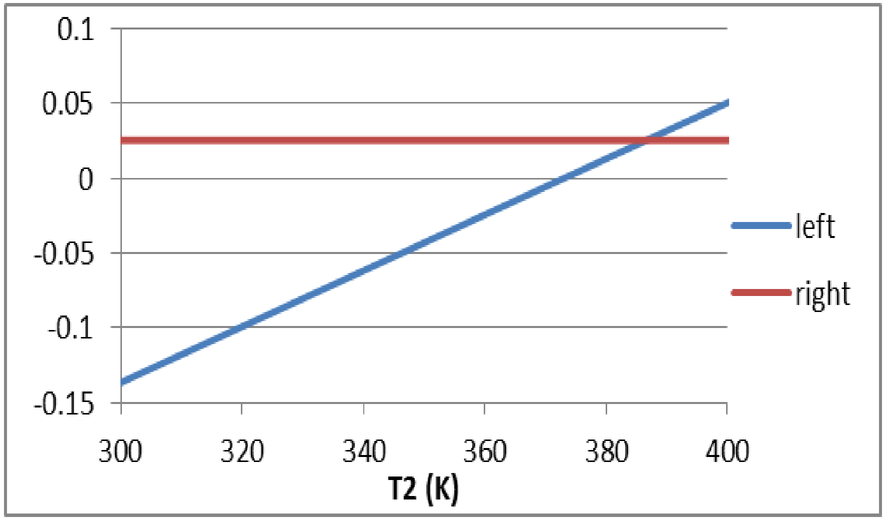
ka	cl	hfg	Pr	mu1	sigma	g	rhol
0.057	4215	2256000	1.76	2.83E-04	5.89E-02	9.807	958

rhog	csf	sigmarad	eps1	eps2	delta	T1	Ts
0.6037	0.013	5.67E-08	0.7	0.9	5.00E-03	1273	373

T2 (K)	left	right
300	-0.13639	0.025571
350	-0.04297	0.025506
400	0.050445	0.02543
390	0.031762	0.025446
380	0.013078	0.025462
385	0.02242	0.025454
386	0.024289	0.025452
387	0.026157	0.025451
386.5	0.025223	0.025452
386.7	0.025596	0.025451
386.6	0.02541	0.025452
386.65	0.025503	0.025451
386.63	0.025466	0.025451
386.62	0.025447	0.025451
386.625	0.025456	0.025451



Excel output