DESIGNING OF DUCT FOR COOLING HEAT GENERATING NUCLEAR FUEL ROD

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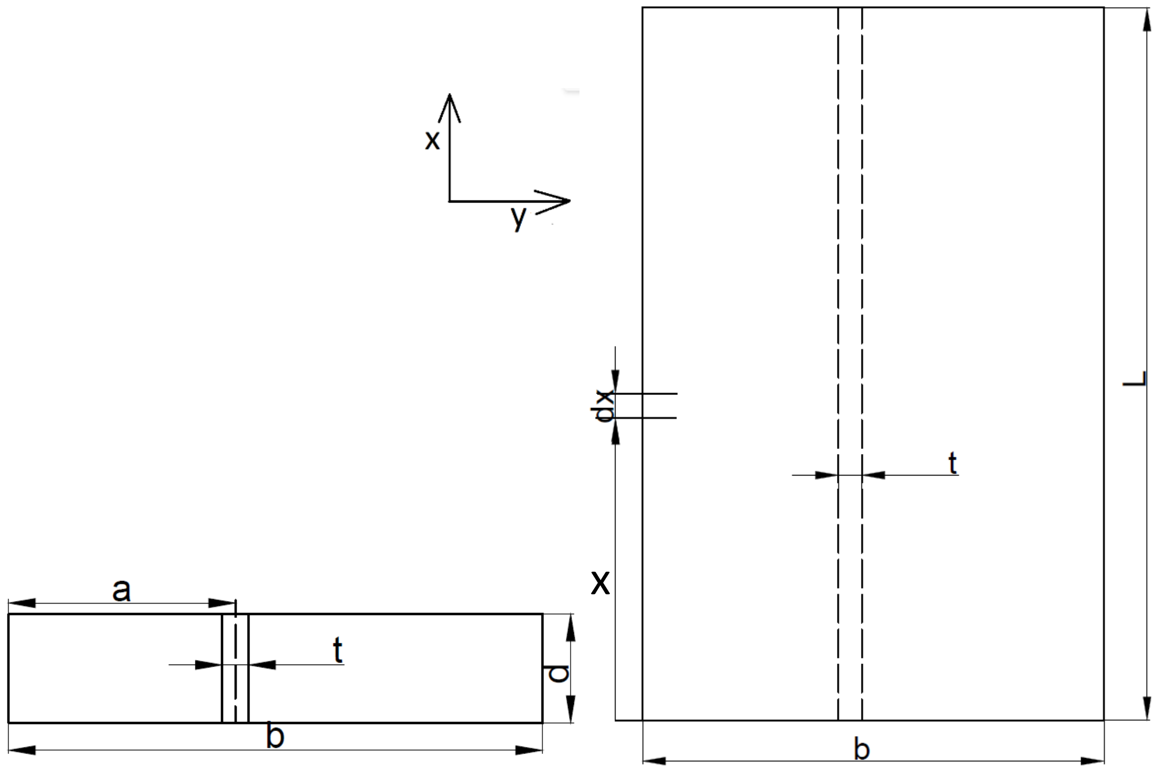
Here in this project, we're trying to simulate a situation where a heat generating element (nuclear fuel rod) is placed in a heat exchanger of a rectangular shaped cross section where the rod can slide in y direction.



Heat generation rate is q W/m^3.

Inlet temperature of coolant is T_i.

Mass flow rate of coolant is $\dot{m}$.

Our objective here is to design the heat exchanger duct so that the rod cools down and its temperature is always under its melting point (with suitable allowances). The problem is approached with suitable assumptions

1. The flow of liquid is fully developed throughout the duct.
2. The rod cools down at steady state.
3. Heat conduction in rod is unidirectional in nature.

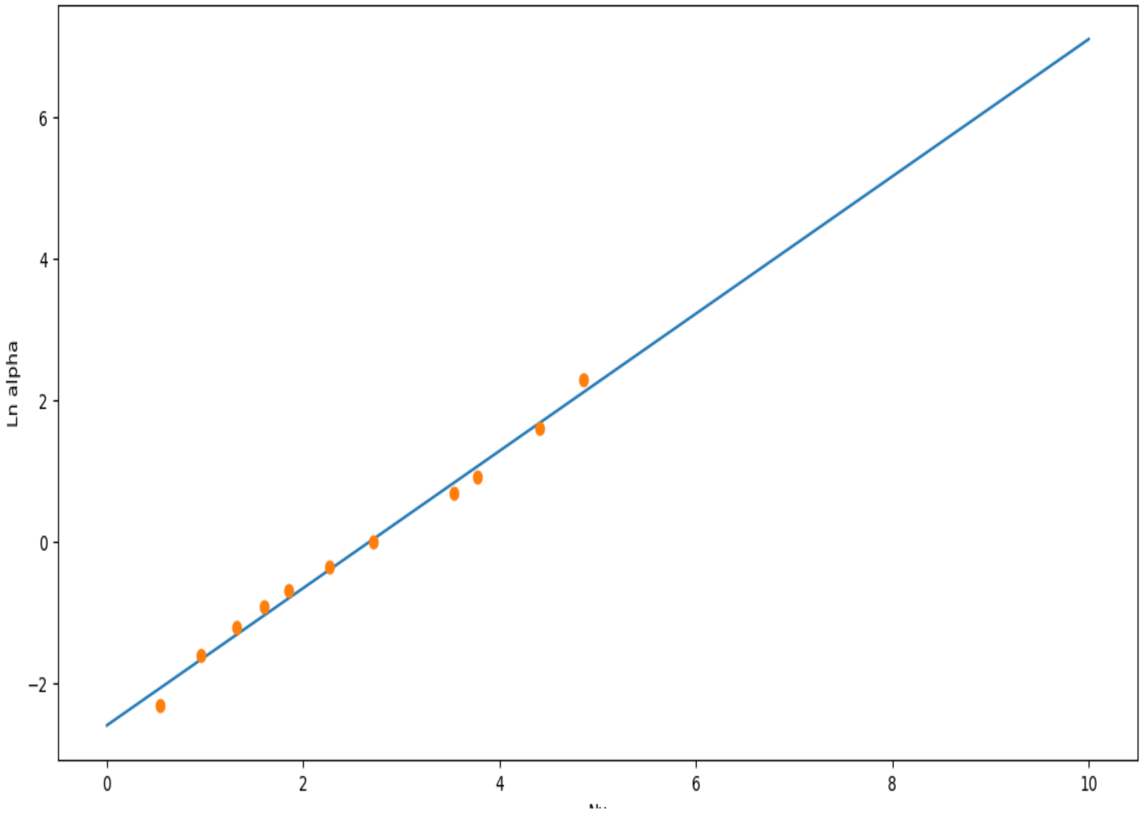
The problem is approached by two means

1. Energy conservation and heat transfer approach.
2. Entropy generation (Second law of thermodynamics) approach.

Energy conservation and heat transfer approach

The aspect ratio (α) is defined as, α=(b/a)

We can get the values of Nusselt numbers and hence the values of the heat transfer coefficients corresponding to different values of aspect ratio. For that we have to use standard handbook of heat transfer. Now for our case we have two rectangular ducts effectively which is insulated in three sides. So, we will use fourth column of table 5.30 & to use the table more elegantly we fit a polynomial of Nusselt no. with corresponding values of Log α.



$$Ln\ \alpha = 0.97\text{Nu} - 2.6$$

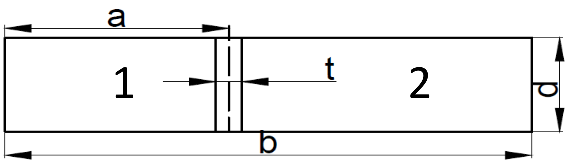
From that after little algebraic manipulation we get two expressions for Nusselt numbers corresponding to each side of the duct.

$$Nu_1 = \frac{1}{0.97}[Ln\left(\frac{d}{a-\frac{t}{2}}\right) + 2.6]$$

$$Nu_2 = \frac{1}{0.97}[Ln\left(\frac{d}{b-a-\frac{t}{2}}\right) + 2.6]$$

The heat generating element effectively divides the duct into two parts. If the total mass flowrate inside the duct is $\dot{m}$ and the mass flow rate in the left side of the duct is $\dot{m}_1$ & the mass flow rate in the rightside of the duct is $\dot{m}_2$, then we can write $\dot{m} = \dot{m}_1 + \dot{m}_2$.

Now as the total pressure drop of both the sides will remain same, we can write



$$\Delta P_1 = \Delta P_2$$

Or, $\frac{f_1 L V_1^2}{2gD_{h1}} = \frac{f_2 L V_2^2}{2gD_{h2}}$

Or, $\left(\frac{V_1}{V_2}\right)^2 = \frac{f_1 D_{h1}}{f_2 D_{h2}}$

Here, D_{h1}&D_{h2} are the hydraulic diameters. f_1&f_2 are the friction factors.

So, we can write D_{h1}=$\frac{4d\left(a-\frac{t}{2}\right)}{2\left(d+a-\frac{t}{2}\right)}$ & $D_{h2} = \frac{4d\left(b-a-\frac{t}{2}\right)}{2\left(d+b-a-\frac{t}{2}\right)}$ from the system geometry.

Now putting the values of D_{h1}& D_{h2} we get

$$\left(\frac{V_1}{V_2}\right)^2 = \frac{f_2\left(a-\frac{t}{2}\right)\left(d+b-a-\frac{t}{2}\right)}{f_1\left(d+a-\frac{t}{2}\right)\left(b-a-\frac{t}{2}\right)} = A$$

$$\frac{V_1}{V_2} = \sqrt{A} = B \quad (Say)$$

Also, we can write $\dot{m}\ as$

$$\dot{m} = \rho\left(d\left(a-\frac{t}{2}\right)\right)BV_2 + \rho\left(d\left(b-a-\frac{t}{2}\right)\right)V_2$$

$$= \rho V_2 d\left[B\left(a-\frac{t}{2}\right) + \left(b-a-\frac{t}{2}\right)\right]$$

From here we get $V_2 = \frac{\dot{m}}{\rho d\left[B\left(a-\frac{t}{2}\right)+\left(b-a-\frac{t}{2}\right)\right]}$

& $V_1 = \frac{B\dot{m}}{\rho d\left[B\left(a-\frac{t}{2}\right)+\left(b-a-\frac{t}{2}\right)\right]}$

And finally, we get the values of $\dot{m}_1$& $\dot{m}_2$

$$\dot{m}_1 = \frac{B\dot{m}\left(a-\frac{t}{2}\right)}{\left[B\left(a-\frac{t}{2}\right)+\left(b-a-\frac{t}{2}\right)\right]} \qquad \& \qquad \dot{m}_2 = \frac{\dot{m}\left(b-a-\frac{t}{2}\right)}{\left[B\left(a-\frac{t}{2}\right)+\left(b-a-\frac{t}{2}\right)\right]}$$

Governing Equation of heat generating element

$$\frac{d^2T}{dy^2} + \frac{q}{K} = 0$$

By integrating

$$\frac{dT}{dy} = \frac{-qy}{K} + C_1 \quad ------(1)$$

$$T = \frac{-qy^2}{2K} + C_1 y + C_2 \quad ------(2)$$

Boundary Conditions

$$-K\frac{dT}{dy}\bigg|_{y=\frac{t}{2}} = h_2\left(T|_{y=\frac{t}{2}} - T_{b2}\right) \quad ------(BC1)$$

$$-K\frac{dT}{dy}\bigg|_{y=\frac{-t}{2}} = h_1\left(T|_{y=\frac{-t}{2}} - T_{b1}\right) \quad ------(BC2)$$

Putting $\frac{dT}{dy}$ and T in boundary conditions and by solving we get the values of C_1 and C_2 as

$$C_1 = \frac{\frac{qt}{2}[h_1 - h_2] + h_1 h_2 [T_{b2} - T_{b1}]}{K(h_1 + h_2) + h_1 h_2 t}$$

$$C_2 = \frac{\left(K + \frac{h_1 t}{2}\right)\left[\frac{qt}{2} + h_2\left(\frac{qt^2}{8K} + T_{b2}\right)\right] + \left(K + \frac{h_2 t}{2}\right)\left[\frac{qt}{2} + h_1\left(\frac{qt^2}{8K} + T_{b1}\right)\right]}{K(h_1 + h_2) + h_1 h_2 t}$$

Now, considering an element dx at a distance along the flow then if increment in base film temperature in that element be dT_{b1} and dT_{b2}.

$$\dot{m}_1 c\, dT_{b1} = q'' d\, dx$$

$$\dot{m}_1 c\, dT_{b1} = -K\frac{dT}{dy}\bigg|_{y=\frac{-t}{2}} d\, dx$$

Now from Boundary condition 2,

$$\dot{m}_1 c\, dT_{b1} = h_1 \left(T|_{\gamma=\frac{-t}{2}} - T_{b1} \right) d\, dx$$

Now putting value of $T|_{\gamma=\frac{-t}{2}}$,

$$\dot{m}_1 c\, dT_{b1} = h_1 d \left[\frac{h_2 q t^2 - 2K h_2 (T_{b1} - T_{b2}) + 2Kqt}{2K(h_1 + h_2) + 2h_1 h_2 t} \right] dx \quad ------(3)$$

Considering $\frac{dT_{b1}}{dx} = DT_{b1}$, and solving we get,

$$\left(\dot{m}_1 cD + \frac{2Kh_1 h_2 d}{2K(h_1 + h_2) + 2h_1 h_2 t} \right) T_{b1} - \frac{2Kh_1 h_2 d T_{b2}}{2K(h_1 + h_2) + 2h_1 h_2 t} = \frac{h_1 h_2 d q t^2 + 2Kqth_1 d}{2K(h_1 + h_2) + 2h_1 h_2 t}$$

$$------(4)$$

Similarly,

$$\dot{m}_2 c\, dT_{b2} = q'' d\, dx$$

$$\dot{m}_2 c\, dT_{b2} = -K \frac{dT}{dy}\bigg|_{y=\frac{t}{2}} d\, dx$$

Now from Boundary condition 1,

$$\dot{m}_2 c\, dT_{b2} = h_2 \left(T|_{\gamma=\frac{t}{2}} - T_{b2} \right) d\, dx$$

Now putting value of $T|_{\gamma=\frac{t}{2}}$, we get

$$\dot{m}_2 c\, dT_{b2} = h_2 d \left[\frac{h_1 q t^2 - 2K h_1 (T_{b2} - T_{b1}) + 2Kqt}{2K(h_1 + h_2) + 2h_1 h_2 t} \right] dx \quad ------(5)$$

Considering $\frac{dT_{b2}}{dx} = DT_{b2}$, and solving we get,

$$\left(\dot{m}_2 cD + \frac{2Kh_1 h_2 d}{2K(h_1 + h_2) + 2h_1 h_2 t} \right) T_{b1} - \frac{2Kh_1 h_2 d T_{b1}}{2K(h_1 + h_2) + 2h_1 h_2 t} = \frac{h_1 h_2 d q t^2 + 2Kqth_2 d}{2K(h_1 + h_2) + 2h_1 h_2 t}$$

$$------(6)$$

From (4) and (6) $\Rightarrow$ Let, $\frac{2Kh_1 h_2 d}{2K(h_1+h_2)+2h_1 h_2 t} = \alpha$;

$$\frac{h_1 h_2 d q t^2 + 2Kqth_1 d}{2K(h_1 + h_2) + 2h_1 h_2 t} = K_1 = Constant;$$

$$\frac{h_1 h_2 d q t^2 + 2Kqth_2 d}{2K(h_1 + h_2) + 2h_1 h_2 t} = K_2 = Constant;$$

So, Equation (4) and (6) becomes,

$$(\dot{m}_1 cD + \alpha)T_{b1} - \alpha T_{b2} = K_1 \quad ------(7)$$

$$(\dot{m}_2 cD + \alpha)T_{b2} - \alpha T_{b1} = K_2 \quad ------(8)$$

Now multiplying equation (7) by $(\dot{m}_2 cD + \alpha)$ and equation (8) by α and then adding :-

$$(\dot{m}_1 cD + \alpha)(\dot{m}_2 cD + \alpha)T_{b1} - \alpha^2 T_{b1} = (\dot{m}_2 cD + \alpha)K_1 + \alpha K_2$$

$$(\dot{m}_1 \dot{m}_2 c^2 D^2 + \dot{m}_1 c\alpha D + \dot{m}_2 c\alpha D + \alpha^2)T_{b1} - \alpha^2 T_{b1} = \alpha(K_1 + K_2)$$

$$\dot{m}_1 \dot{m}_2 c^2 \frac{d^2 T_{b1}}{dx^2} + (\dot{m}_1 + \dot{m}_2)c\alpha \frac{dT_{b1}}{dx} = \alpha(K_1 + K_2) \quad ------(9)$$

Now multiplying equation (7) by α and equation (8) by $(\dot{m}_1 cD + \alpha)$ and then adding :-

$$\dot{m}_1 \dot{m}_2 c^2 \frac{d^2 T_{b2}}{dx^2} + (\dot{m}_1 + \dot{m}_2)c\alpha \frac{dT_{b1}}{dx} = \alpha(K_1 + K_2) \quad ------(10)$$

Solving Equation (9) and (10), we get

$$T_{b1} = C_1 + C_2 e^{-\frac{(\dot{m}_1 + \dot{m}_2)x}{\dot{m}_1 \dot{m}_2 c}} + \frac{\alpha(K_1 + K_2)}{\dot{m}_1 + \dot{m}_2} x \quad ------(11)$$

$$T_{b2} = C_1' + C_2' e^{-\frac{(\dot{m}_1 + \dot{m}_2)x}{\dot{m}_1 \dot{m}_2 c}} + \frac{\alpha(K_1 + K_2)}{\dot{m}_1 + \dot{m}_2} x \quad ------(12)$$

Now we are solving Equation (11) and (12) by applying Boundary Conditions :-

$$T_i = C_1 + C_2 \quad ------(13)$$

$$T_i = C_1' + C_2' \quad ------(14)$$

$$\begin{aligned}\dot{m}_1 c[(C_1 + C_2 e^{-aL} + bL) - T_i] \\ = \frac{h_1 d}{2K(h_1 - h_2) + 2h_1 h_2 t}\Bigg[-qt^2 h_2 L - 2KqtL \\ + 2Kh_2\left\{(C_1 - C_1')L - \frac{e^{-aL}}{a}(C_2 - C_2')\right\}\Bigg] \quad ------(15)\end{aligned}$$

$$\dot{m}_2 c[(C_1' + C_2' e^{-aL} + bL) - T_i]$$
$$= \frac{h_2 d}{2K(h_1 - h_2) + 2h_1 h_2 t}\left[-qt^2 h_1 L - 2KqtL + 2Kh_1\left\{(C_1 - C_1')L - \frac{e^{-aL}}{a}(C_2 - C_2')\right\}\right] \quad ------(16)$$

Where

$$a = \frac{(\dot{m}_1 - \dot{m}_2)\alpha}{\dot{m}_1 \dot{m}_2 c}$$

$$b = \frac{K_1 - K_2}{c(\dot{m}_1 - \dot{m}_2)}$$

$$T_i = 25℃$$

Now, we have four unknowns (C_1, C_2, C_1', C_2') and four equations, hence we can solve the above equations to get the value of unknowns.

Entropy generation approach :-

In this problem we're to find the degree of irreversibility by calculating the entropy generation. The lesser irreversibility will refer to lesser loss of available energy in the process.

Now if we consider dx element at a distance x along the flow and ds_1, ds_2, dS_{gen1}, dS_{gen2} be total change in entropy and the entropy generation in left hand and right-hand side respectively then for left hand side,

$\dot{m}_1 ds_1 = \frac{q'' d dx}{T_{s_1}} + dS_{gen_1}$ -----------(i)

Now if dh1 be the enthalpy change then

$\dot{m}_1 dh_1 = q'' d dx$

Now we know

$T_{b1} ds_1 = dh_1 - v_1 dP_1$

$ds_1 = \frac{dh_1}{T_{b1}} - \frac{v_1 dP_1}{T_{b1}}$

$\dot{m}_1 ds_1 = \dot{m}_1 (\frac{dh_1}{T_{b1}} - \frac{v_1 dp_1}{T_{b1}})$

$\dot{m}_1 ds_1 = \frac{1}{T_{b1}} (q'' d dx - \dot{m}_1 v_1 dp_1)$ -----------------(ii)

From (i) and (ii) we've

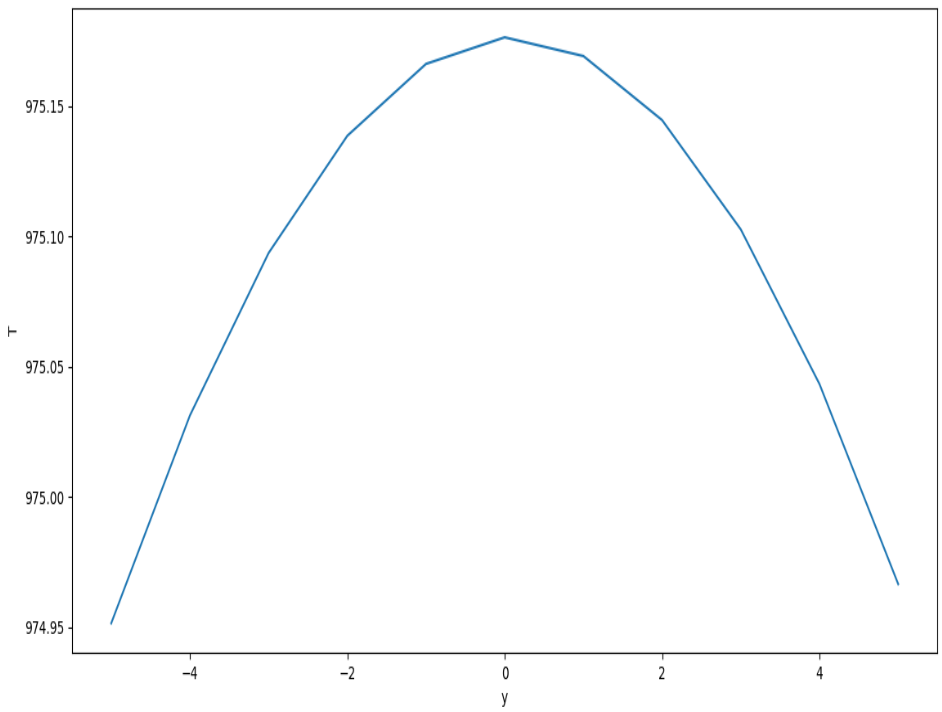
$dS_{gen_1} = q''_1 d dx \left(\frac{1}{T_{b1}} - \frac{1}{T_{s1}}\right) - \dot{m}_1 \frac{v_1 dP_1}{T_{b1}}$

We can find q'' by considering the steady state condition

$$\dot{m}_1 c (T_{exit1} - T_0) = q'' * d * L$$

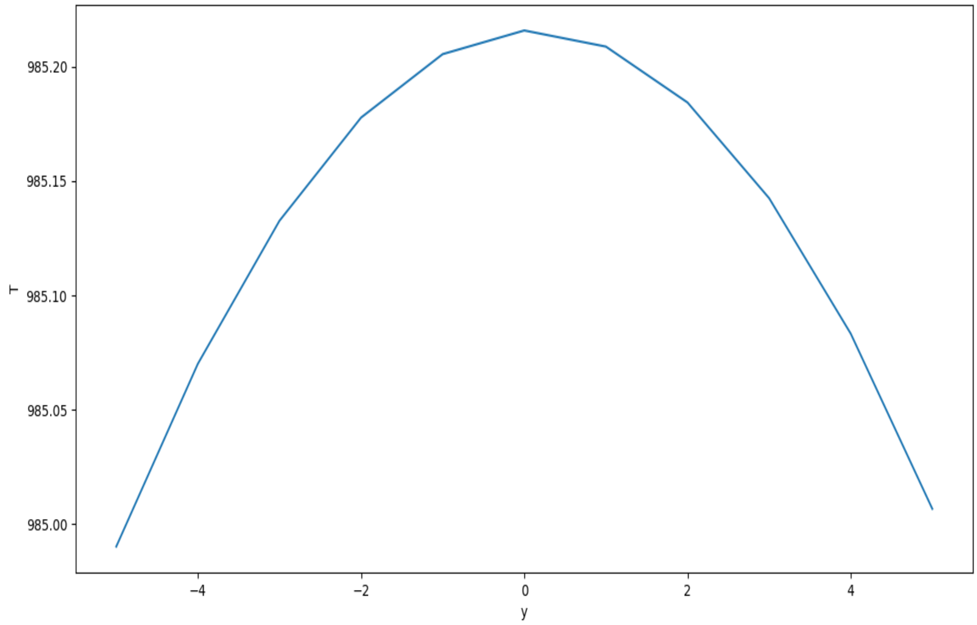
Now similarly we can find entropy generation for right hand side and by adding them up we can find the entropy generation in each case.

- **Results :-** Throughout the problem our objective was to make sure that the maximum temperature rise of the heat generating element remains lower than the melting point temperature of the element of which it is made off. For that we have to know temperature profile in the heat generating element. We have taken two cases , one at the inlet and one at the outlet. The corresponding profiles are as follows.



Temperature profile inside the heat generating element at inlet

(t=10mm, b=550mm, k(element)=23W/mK, q=400KJ/m^3, c=4184 J/KgK, Ti=298K, L=2m, mass flow rate=10Kg/m^3, d=40mm)



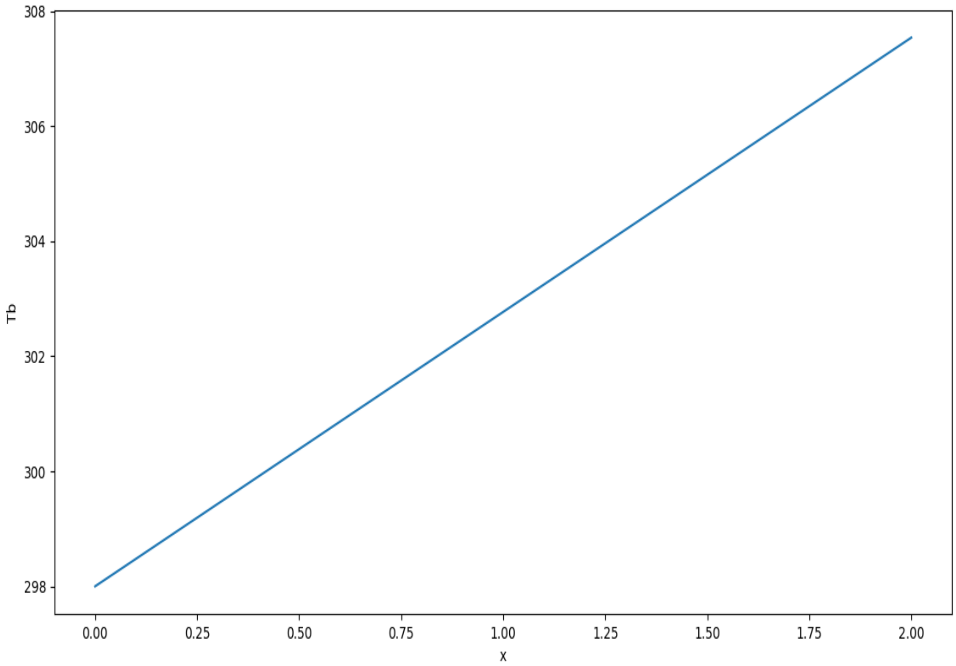
Temperature profile inside heat generating element at outlet

(t=10mm, b=550mm, k(element)=23W/mK, q=400KJ/m^3, c=4184 J/KgK,

Ti=298K, L=2m, mass flow rate=10Kg/m^3, d=40mm)

From these two curves we see that the maximum temperature inside the element happens somewhere in the middle. And the maximum temperature is maximum at the outlet. So we shall try to minimize this temperature.

Also we will keep track of the temperature of the coolant which in our case is water. We will make it sure that it does not vaporize. And the profile of that temperature along the length is coming out to be:



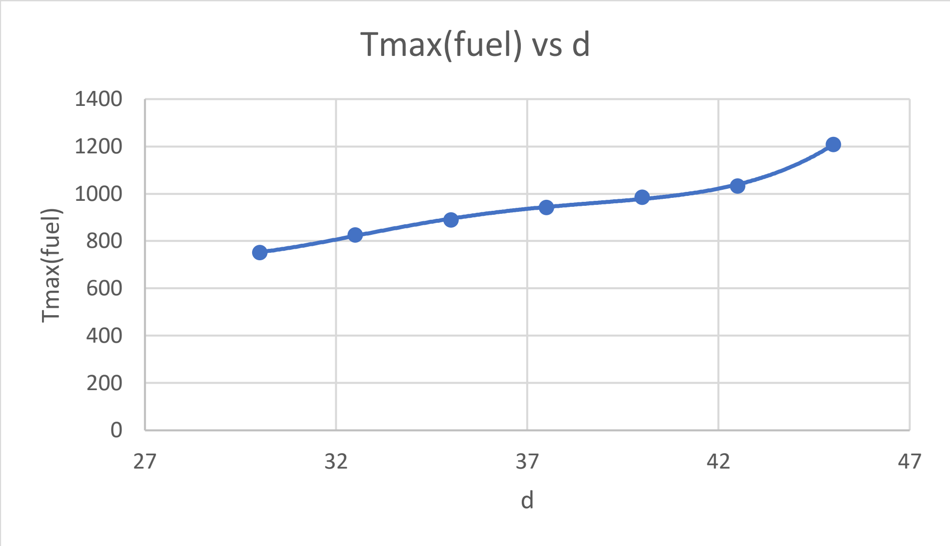
Here we see that the maximum temperature rise of the water is below its boiling point (373K).

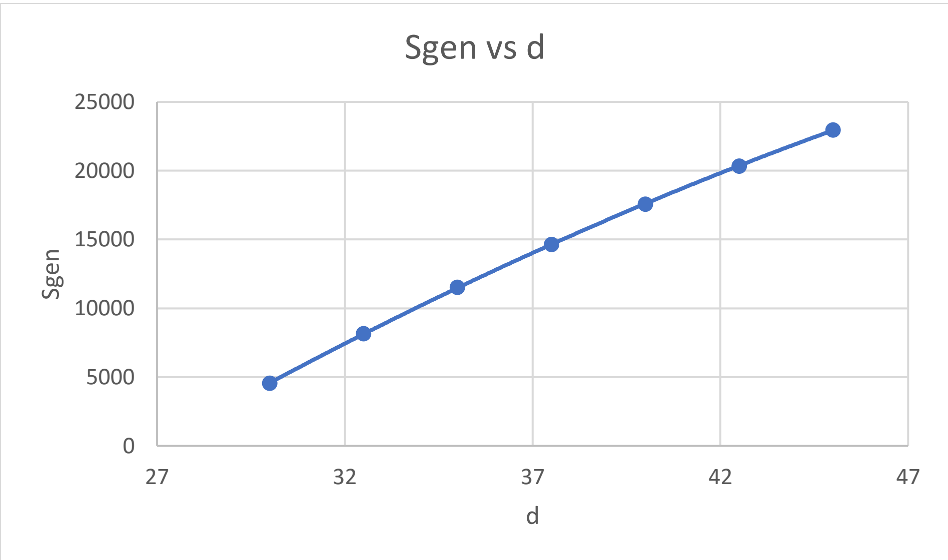
Parametric Variation :-

Now as it's evident that the results are pretty much dependent and governed by the design parameters of the problem an attempt has been made to establish relationship of max temp of heat generating element and also the Entropy generation in the process with the various parameters as stated below when the rod is placed at mid position in the duct.

- Variation of depth :-

d(mm)	T_{max} (fuel)	S_{gen}(J/K)
40	985.5228	17568.31
35	889.7746	11513.86
45	1208.766	22959.23
37.5	942.2955	14637.09
42.5	1033.735	20334.92
30	752.0967	4546.115
32.5	826.6328	8164.522

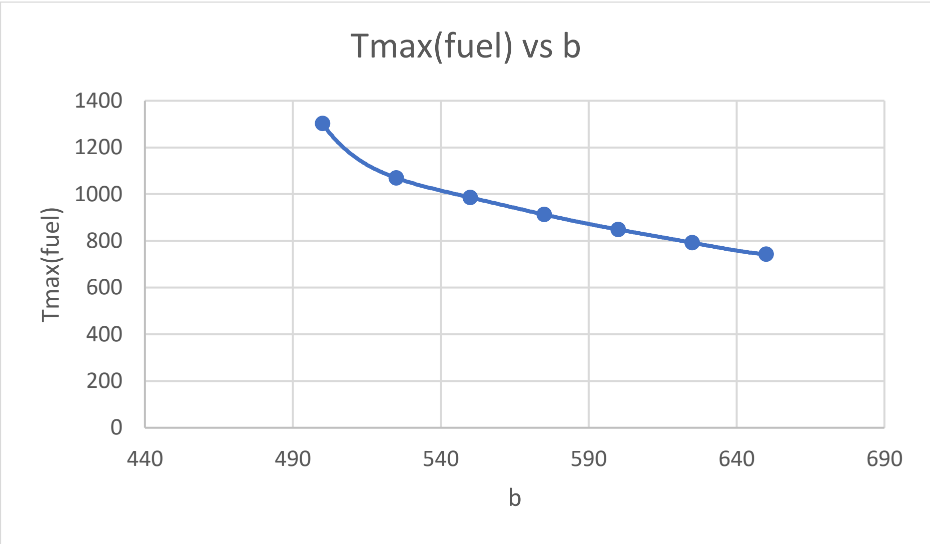


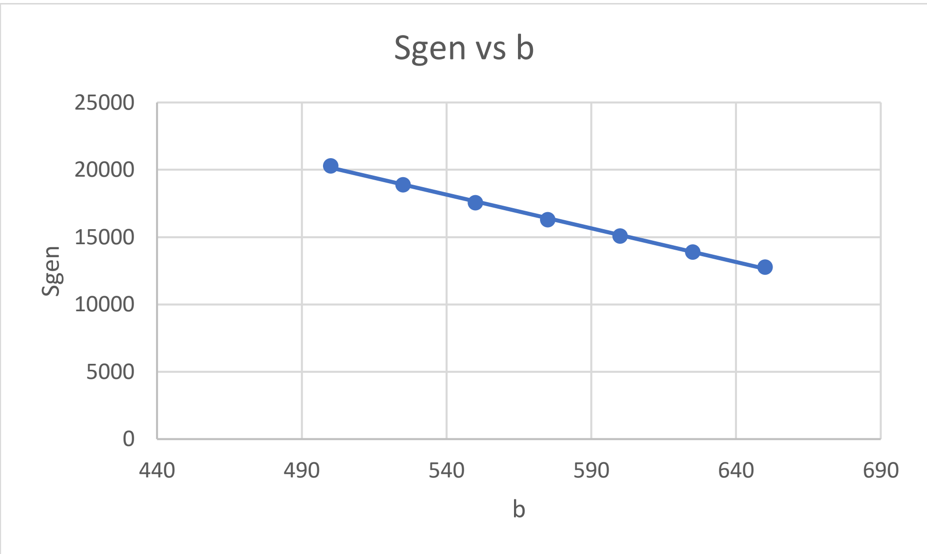


As we increase the depth of the duct it's evident that both the max temperature of fuel and entropy generation increases. Hence our objective will be best fulfilled when d is as low as possible.

➢ Variation of breadth:

b (mm)	T_{max} (fuel)	S_{gen}(J/K)
550	985.5228	17568.31
500	1301.672	20296.63
600	848.3902	15076.15
650	742.578	12785.49
625	792.0769	13907.5
575	912.4813	16295.06
525	1069.002	18900.45

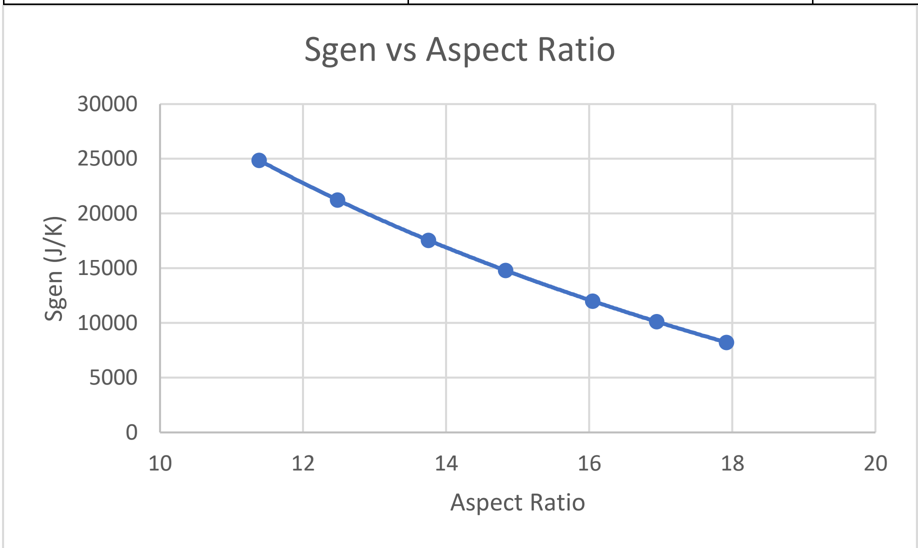


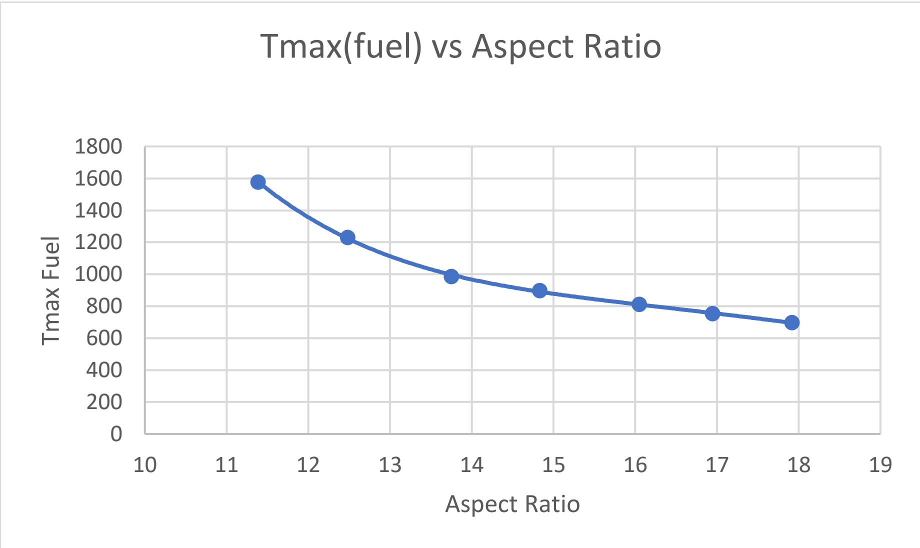


On the contrary when breadth is increased both the maximum temperature and entropy generation decreases. Hence while designing we should go for a higher breadth based on other constraints present. So wider the duct more favourable it is.

➢ Variation of Aspect ratio :-

Aspect Ratio	T_{max} (fuel)	S_{gen}(J/K)
13.75	985.5228	17568.31
17.91837	697.1565	8224.64
16.04821	811.1229	11999.85
16.94444	753.5026	10119.53
12.48299	1229.899	21234.64
11.3843	1576.891	24877
14.83218	898.4559	14796.3

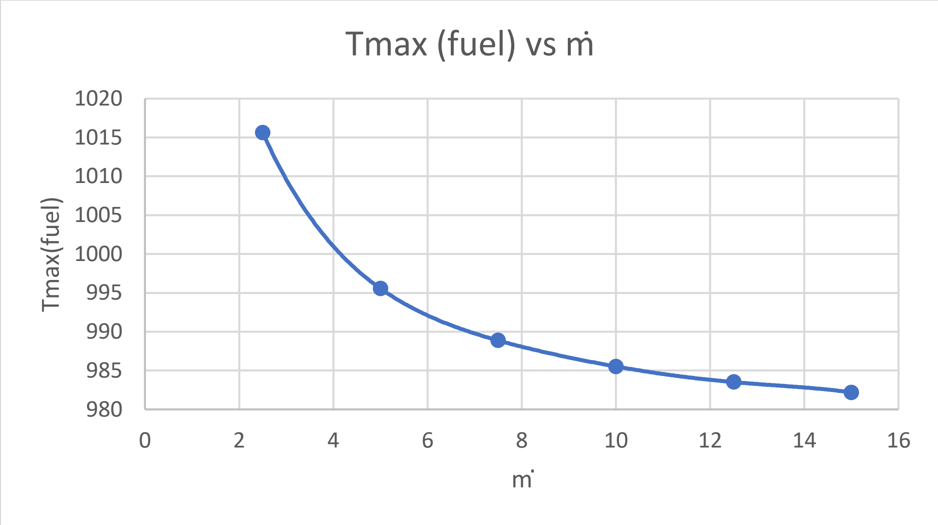


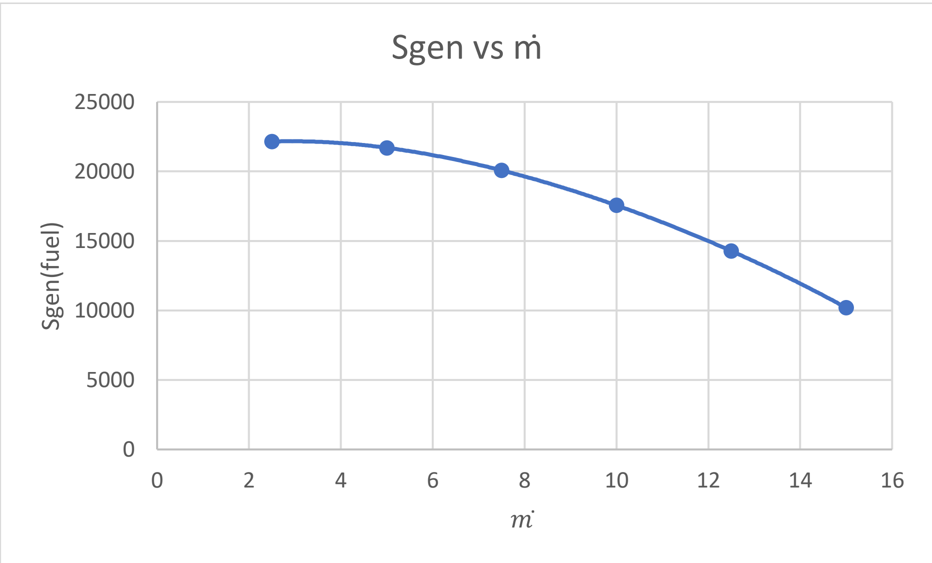


Now to generalise the last two studies we've developed a relationship with the aspect ratio (b/d) while keeping the volume constant to a value 0.02 m^3. Now we see that with increase with aspect ratio both maximum temperature and entropy generation decreases. As it can be related with increase in b and/or decrease in d simultaneously. Hence biggest the b/d ratio better the design is.

➢ Variation of mass flow rate:

$\dot{m}$	T_{max} (fuel)	S_{gen}(J)
10	985.5228	17568.31
5	995.5566	21702.97
7.5	988.8678	20068.75
2.5	1015.614	22146.98
12.5	983.5156	14270.67
15	982.1775	10199.48

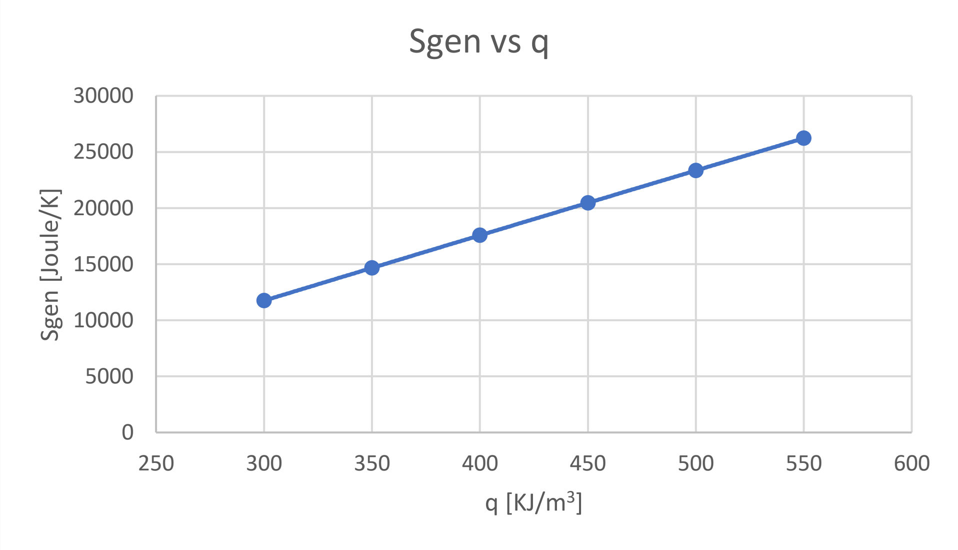


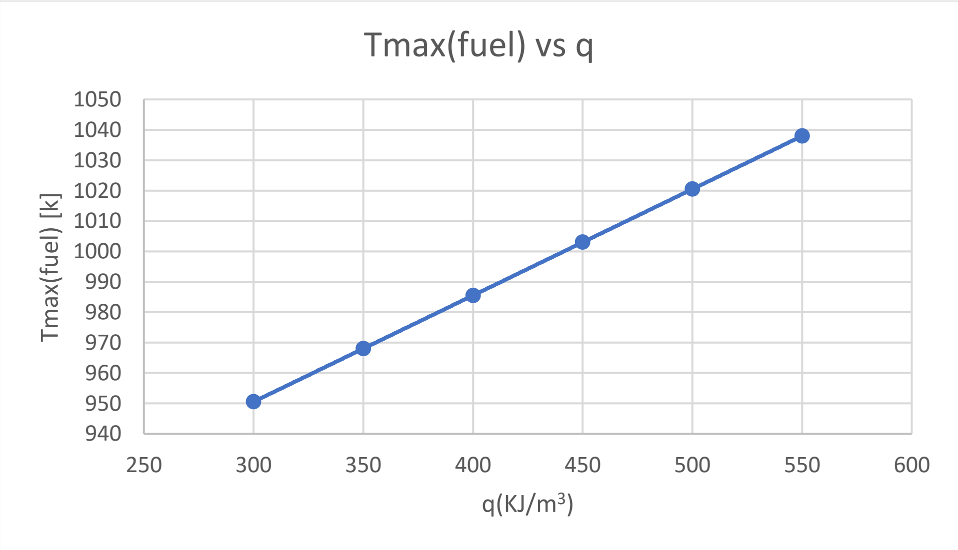


In this problem basically due to convection heat transfer the heat generated in the nuclear fuel rod gets dissipated into flowing coolant under steady state. Now we can see that with increase in mass flow rate of coolant both maximum temperature and entropy generation decreases as the heat transfer coefficient increases with increase in flow rate in convex downwards and concave downwards fashion respectively.

- Variation of heat generation :-

q (KJ/m^3)	T_{max} (fuel)	S_{gen}(J)
400	985.5228	17568.31
300	950.5549	11746.96
350	968.0388	14663.3
450	1003.007	20462.07
500	1020.491	23344.66
550	1037.975	26216.18

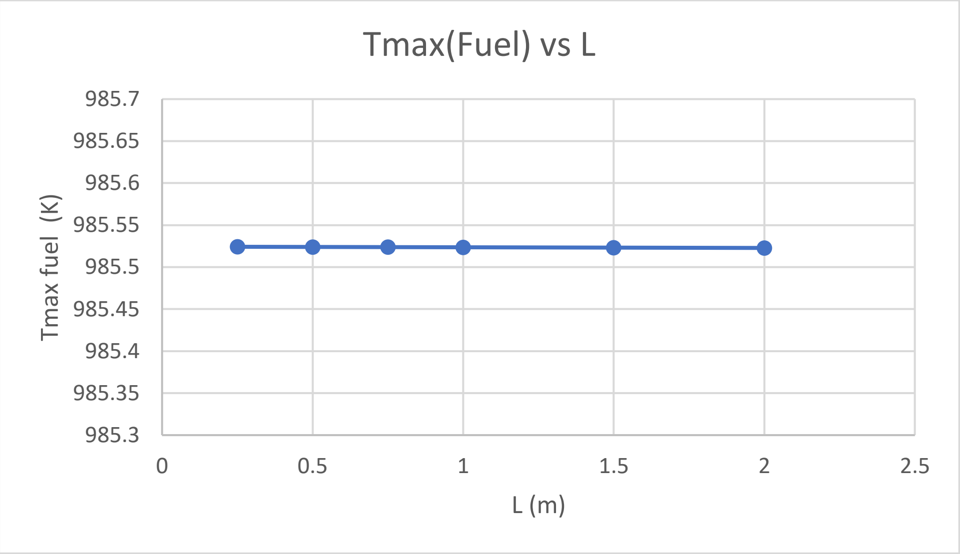


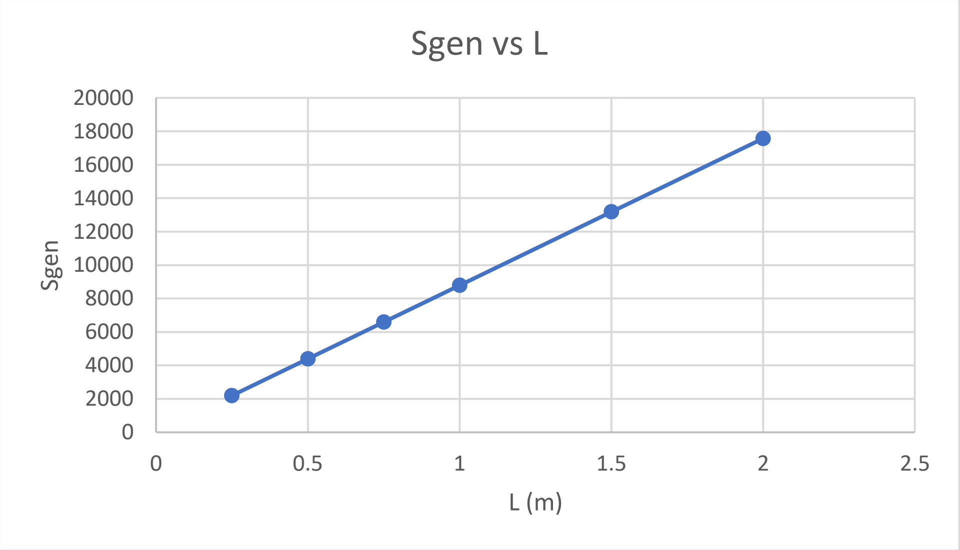


With increase in heat generation internal temperature of fuel increases.we can see that with increase in heat generation both maximum temperature and entropy generation increases.

➢ Variation of length :-

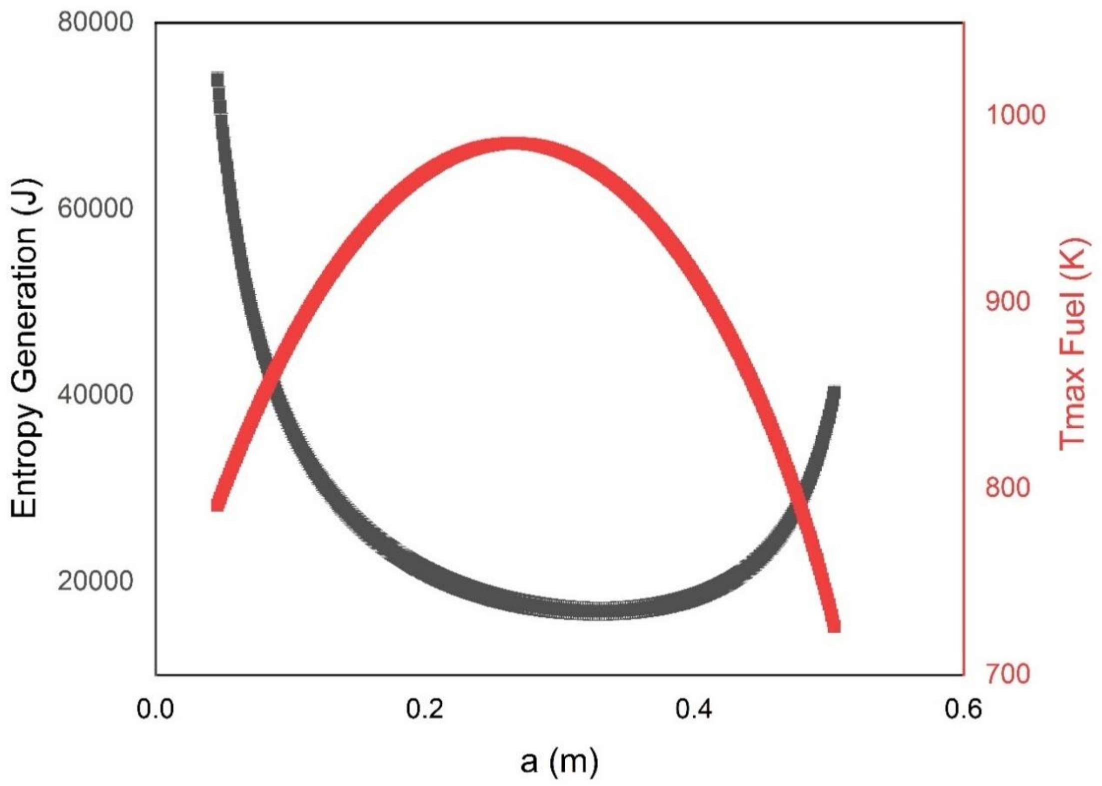
L (mm)	T_{max} (fuel)	S_{gen}(J)
0.25	985.5242	2196.043
0.5	985.524	4392.085
0.75	985.5238	6588.126
1	985.5236	8784.165
1.5	985.5232	13176.24
2	985.5228	17568.31





With increase in length an interesting result is obtained. As it’s evident that under steady state length will have minimal effect on maximum temperature as eventually all the heat is taken out in every case. Still the irreversibility decreases significantly when the length is comparatively small. Hence if the length of the duct is smaller there will be lesser loss in available energy.

Variation of output by variation of relative position of Fuel rod (variation of a) :-



All the data we've collected this far has been calculated considering the fact that the heat generating element is placed at mid position. Now we're to simulate the max temperature and entropy generation by moving the rod in various positions. In this case we see that the profile of max temperature of fuel is maximum at mid position and it decreases while rod is moved to a more extreme position. We see that the maximum possible value of rod is 985 K(approx.) is well below it's (Hf) melting point (2500 k)

On the other hand, for these inputs the min entropy generation is observed when fuel rod is placed at a distance 329 mm from the left-hand side, bearing entropy generation of 16.845 KJ/K.

Now as the melting point is well above the operating temperature at any position, we should go for placing the rod at the position having minimum irreversibility as pumping power will be less loss in available energy. But if is some cases it's observed that the fuel Temperature is reaching close to its melting point then we would have to move the rod rightwards to avoid melting.

- **Conclusion :-** Now from practical point of view the aspect ratio and mass flow rate of coolant (water in our case) is the two most significant input variables in our hands. While designing these two parameters should be chosen wisely keeping the relationships in mind.

Submission of Code :-

```
from scipy.optimize import fsolve ## importing required modules
import numpy as np
import math
import matplotlib.pyplot as plt
def my_function(Z):
    X=Z[0]
    Y=Z[1]
    C=Z[2]
    D=Z[3]
    F=np.empty(4)
    F[0]=T-X-Y #X=c1,Y=c2
    F[1]=T-C-D #C=c1',D=c2'
    F[2]=(E*c*(X+(Y*math.exp(-H*L))+(I*L)-T))+(h1*d*((2*k*h2*(((X-C)*L)-
(math.exp(-H*L)*(Y-D)/H)))-(q*t*t*h2*L)-
(2*k*q*t*L))/((2*k*(h1+h2))+(2*h1*h2*t)))+(G*c*(C+(D*math.exp(-H*L)-1)+(I*L)-
T))-(h2*d*((2*k*h1*(((X-C)*L)-((math.exp(-H*L)-1)*
(Y-D)/H)))+(q*t*t*h1*L)+(2*k*q*t*L))/((2*k*(h1+h2))+(2*h1*h2*t)))
    F[3]=(E*c*(X+(Y*math.exp(-H*L))+(I*L)-T))+(G*c*(C+(D*math.exp(-
H*L))+(I*L)-T))-q
    return F
## Input of variables
d1=float(input('d in mm ='))
t1=float(input('t in mm= '))
b1=float(input('b in mm= '))
k=float(input('thermal conductivity= '))
T=float(input('ti= '))
m=float(input('m dot= '))
L=float(input('length= '))
q=float(input('q= '))
c=float(input('c='))
t=0.001*t1
d=0.001*d1
b=0.001*b1
Tmax=0.0
array=[] ##list to contain all possible position of fuel rod
a1=b/2
```

```
while(a1>=d+(t/2)):   ###injecting values of a in array
    array.append(a1)
    a1=a1-0.001
a1=(b/2)+0.001
while(a1<=b-d-(t/2)):
    array.append(a1)
    a1=a1+0.001
array.sort()
Y=[0]
Tsmaxi=0.0
Tsmaxo=0.0
y=-t/2
while(y<=(t/2)):     ##loop run to obtain temperature at various positions
inside the rod
    Y.append(y)
    y=y+0.001
To1L=[]
To2L=[]
TSi=[]
TSo=[]
n=int(len(array)/2)
mid1=int(n-1)
mid2=n-1
Tmi=2500  ###melting point of Hafnium
Tmo=2500
sgenmin=80000.00
SGEN=[]   ##list to contain entropy generation at different a
for a in array:
    ### Calculating required parameters
    alp1=d/(a-t/2)
    alp2=d/(b-a-t/2)
    nu1=((math.log(d/(a-t/2),math.exp(1))+2.6)/0.97)  ##nusselt numbers
    if(nu1>5.384):
        nu1=5.384
    nu2=((math.log(d/(b-a-t/2),math.exp(1))+2.6)/0.97)
    if(nu2>5.384):
        nu2=5.384
    di1=4*d*(a-t/2)/(2*(d+(a-t/2))) ##hydraulic diameters
    di2=4*d*(b-(a-t/2))/(2*(d+(b-a-t/2)))
    f1=24*(1-1.3553*alp1+1.9467*alp1**2-1.7012*alp1**3+0.9564*alp1**4-
0.2537*alp1**5)#friction factors
    f2=24*(1-1.3553*alp2+1.9467*alp2**2-1.7012*alp2**3+0.9564*alp2**4-
0.2537*alp2**5)
    h1=(nu1*k/di1)   #heat transfer coefficients
    h2=(nu2*k/di2)
    M=(((h1*d*q*t*t*h2)+(2*k*q*t*h1*d))/((2*k*(h1+h2))+(2*h1*h2*t)))#k1
    N=(((h1*d*q*t*t*h2)+(2*k*q*t*h2*d))/((2*k*(h1+h2))+(2*h1*h2*t)))#k2
    J=(((2*k*h1*h2*d)/((2*k*(h1+h2))+(2*h1*h2*t))))#alpha
```

```
    A=(f2/f1)*((a-(0.5*t))/(d+a-(0.5*t)))*((d+b-a-(0.5*t))/(b-a-(0.5*t)))
    ## mass flow rates
    E=((m*(math.sqrt((f2*(a-(0.5*t))*(d+b-a-(0.5*t)))/(f1*(d+a-(0.5*t))*(b-a-
(0.5*t)))))*(a-(0.5*t))/(((math.sqrt((f2*(a-(0.5*t))*(d+b-a-
(0.5*t)))/(f1*(d+a-(0.5*t))*(b-a-(0.5*t)))))*(a-(0.5*t)))+(b-a-(0.5*t))))) #m1
    G=m*(b-a-(0.5*t))/((math.sqrt(A)*(a-(0.5*t)))+(b-a-(0.5*t)))#m2
    H=(((E+G)*J)/(E*G*c)) #a
    I=((M+N)/((c*E)+(c*G))) #b
    ZGuess=np.array([100,1,1,1])
    Z = fsolve(my_function,ZGuess)  ##calling f solve to solve integration
constants in Tb1 Tb2
    To1=Z[0]+Z[1]*math.exp(-H*L)+I*L ##outlet temperature of coolant
    To2=Z[2]+Z[3]*math.exp(-H*L)+I*L
    P=((q*t/2)*(h1-h2))/(k*(h1+h2)+(t*h1*h2)) #c1
    Q=(((h1*t/2)+k)*((q*t/2)+h2*((q*t**2/8*k)+T))+((h2*t/2)+k)*((q*t/2)+h1*((q
*t**2/8*k)+T)))/(k*(h1+h2))+h1*h2*t #c2 at inlet
    R=(((q*t/2)*(h1-h2))+h1*h2*(To2-To1))/(k*(h1+h2)+(t*h1*h2)) #c1
    S=(((h1*t/2)+k)*((q*t/2)+h2*((q*t**2/8*k)+To2))+((h2*t/2)+k)*((q*t/2)+h1*(
(q*t**2/8*k)+To1)))/(k*(h1+h2))+h1*h2*t #c2 at outlet
    TS=[]
    for y in Y:   ##calculating interior temp of rod
        Tsi=(-q/k)*0.5*y**2+P*y+Q
        Tso=(-q/k)*0.5*y**2+R*y+S
        if (y==-(t/2) or y==(t/2)):
              TS.append(Tsi)
              TS.append(Tso)
        if (Tsi>Tsmaxi):
            Tsmaxi=Tsi
            maxposi=y
        if (Tso>Tsmaxo):
            Tsmaxo=Tso
            maxposo=y
    if a>(b/2):
        Tsmaxi=TSi[mid2]
        Tsmaxo=TSo[mid2]
        mid2=mid2-1
    if a==(b/2):     ##finding max temp when rod placed at mid point
        TM=[Tsmaxi,Tsmaxo]
        TT=Tsmaxo

    if Tsmaxi<Tmi:      ## comparing temperature w.r.t melting point and
finding out min possible value of Tmax(fuel) at diff a
        Tmi=Tsmaxi
        ai=a
        Zi=Z
        Hi=H
        Ii=I
    if Tsmaxo<Tmo:
```

```
        Tmo=Tsmaxo
        ao=a
        Zo=Z
        Ho=H
        Io=I
        TB=[To1,To2]
    TSi.append(Tsmaxi)
    TSo.append(Tsmaxo)
    To1L.append(To1)
    To2L.append(To2)
    x=0.5*10**(-3)
    sgen1=0.0
    sgen2=0.0
    while(x<L):     ### calculating entropy generation
        Tb1=Z[0]+Z[1]*math.exp(-H*x)+I*x
        Tb2=Z[2]+Z[3]*math.exp(-H*x)+I*x
        c1=(((q*t/2)*(h1-h2))+h1*h2*(Tb2-Tb1))/(k*(h1+h2)+(t*h1*h2))
        c2=((h1*t/2)+k)*((q*t/2)+h2*((q*t**2/8*k)+Tb2))+((h2*t/2)+k)*((q*t/2)+
h1*((q*t**2/8*k)+T))/((k*(h1-h2))+h1*h2*t)
        Ts1=(-q/k)*0.5*(-t/2)**2+c1*(-t/2)+c2
        Ts2=(-q/k)*0.5*(t/2)**2+c1*(t/2)+c2
        sgentemp1=h1*(h2*q*t**2+2*k*q*t-2*k*h2*(Tb1-
Tb2)/(2*k*(h1+h2)+2*h1*h2*t))*d*0.001*((1/Tb1)-(1/Ts1))-
E*f1*0.001*(E/(1000*(a-0.5*t)*d)**2/2*9.81*di1*1000)
        sgentemp2=h2*(h1*q*t**2+2*k*q*t-2*k*h1*(Tb2-
Tb1)/(2*k*(h1+h2)+2*h1*h2*t))*d*0.001*((1/Tb2)-(1/Ts2))-
G*f2*0.001*(E/(1000*(b-a-0.5*t)*d)**2/2*9.81*di2*1000)
        sgen1+=sgentemp1
        sgen2+=sgentemp2
        x+=0.001
    sgen=sgen1+sgen2
    SGEN.append(sgen)
    if a==(b/2):      ##obtaining entropy generation, various integration
constants while a=(b/2)
        SM=sgen
        TSC=[P,Q,R,S]
        TBC=Z
        TBI=[H,I]
        TBO=[To1,To2]
    if (sgen<sgenmin):   ## calxulating min possible entropy generation
        sgenmin=sgen
        minp=a
    'following commands print outlet temp, max temp of fuel rod, temp of rod
at surface etc for every value of a  '
    # print(To1,To2,end="\t")
    # print(Tsmaxi,maxposi,end="\t")
    # print(Tsmaxo,maxposo,end="\t")
    # print(TS)
```

```
print(ai,ao,Tmi,Tmo)    ##prints max temperatues and corresponding location inside rod
print(TT,SM,(b1/d1))    ## prints Max temp,entropy generation at mid posion, aspect ratio of duct
print(sgenmin,minp)     ## prints min possible entropy generation
print(TBC,TBI,TBO)      ## prints basic information to find out profile of rod temp and base temp
```