Thermal Analysis of Convection and Radiation in Finned Heat Exchanger

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ABSTRACT:
The object of this study is to analyze the heat exchanging fins and to show the effects of convection and radiation in heat transfer model on a catalytic reactor. Reactant gas enters the catalytic reactor path and heat transfer in the stainless steel profile is studied. Due to symmetry, one of the walls may used. The temperature of reactor surface and the temperature profile of fin can be estimated by simulation using ANSYS. The temperature profiles of radiation show different aspects. The radiation term did not affect the temperature profile for this reason the radiation can be ignored in the forced convection system. On the other hand, the calculation of natural convection shows similar result to ANSYS result. However, in forced convection, the manual calculation is lower than that of ANSYS. Even though the temperature profile of forced convection has differences between ANSYS and manual calculations, the temperatures at the end of the fin are same. From above, the radiation term is important in natural convection system.
For the effect of material properties, the material is changed from steel AISI 4340 to aluminum. The temperature at the surface of the aluminum wall is 150K higher than that of steel.

الخلاصة

إنّ هدفَ هذه الدراسةِ هو تُحلّلَ الزعانفَ المبادلات الحرارية وبيان تأثيراتِ الحملِ والإشعاعِ في نموذجِ انتقال الحرارةِ على مفاعل تحفيزي.وتم دراسة انتقال الحرارةِ من الغاز المتفاعل الذي يدخل المفاعل، وكذلك تم الدراسة على جدار واحد للمفاعل نتيجة للتشابه. تم استخدام برنامج متطور (ANSYS) لإيجاد توزيع درجات الحرارة في زعنفة طولية على جدار المفاعل . ان مخططات درجة الحرارة تبين ان الإشعاعِ له سماتَ مختلفةَ. حيث بينت النتائج عدم تأثير الإشعاعَ على مخططات درجة الحرارة في نظامِ الحملِ القسريِ بينما لا يمكن إهماله في حالة الحمل الحر. من الناحية الأخرى، حسابَ الحملِ الطبيعيِ يبين النَتيجةِ المماثلةِ إلى نتيجةِ ANSYS. بينما في الانتقال القسريِ، الحسابات النظرية أقل دقة من ANSYS . بالرغم من أنَّ درجات الحرارة في نهايةِ الزعنفةِ نفسها.
اما بالنسبة الى تأثير خواص المواد، فتم استخدام AL في بناء المبادل بدلا من steel AISI 4340.

Keywords / Heat Exchanger, fins, catalytic reactor, forced and natural convection system, parametric stud

1-INTRODUCTION

Heat exchangers are commonly used in many fields of industry, which are composed of finned surfaces for dissipation of heat by convection and conduction. The calculation of heat transfer of a cooling fin in heat exchanger system is the good practical application of heat transfer. Such fins are used to increase the cooling area of system available for heat transfer between metal walls and conducting fluid such as gases and liquds[1]. In a chemical process, the reactor at hot temperature is cooled using cooling fins. The coolant is the surrounding air. Heat transfer in heat exchanger is dominated by convection from the surfaces, although the conduction within the fin may also influence on the performance. A convenient method to treat convection cooling is to use heat transfer coefficients, h[2].

A system is catalytic reactor with heat exchanging fins (Fig.1), which is a monolithic bed reactor for autothermal reaction (ATR). As the reactant gas is introduced into the monolithic ATR reactor, the reaction occurs along the monolith, but the temperature in the reactor is not uniform. The temperature of inlet end rises rapidly, and then gradually decreases. The wall thickness and the length of the heat exchanger are 0.25m and 8m, respectively. The dimensions of fins are 0.4*1m. During operation, the temperature inside the wall is maintained. The heat is conducted within the fins and then transferred to the surrounding air. As the air is heated, buoyancy effects cause heat to transport upward by heated air which rises (natural convection heat transfer) or heat sweep to right by forced stream of air (forced convection heat transfer).

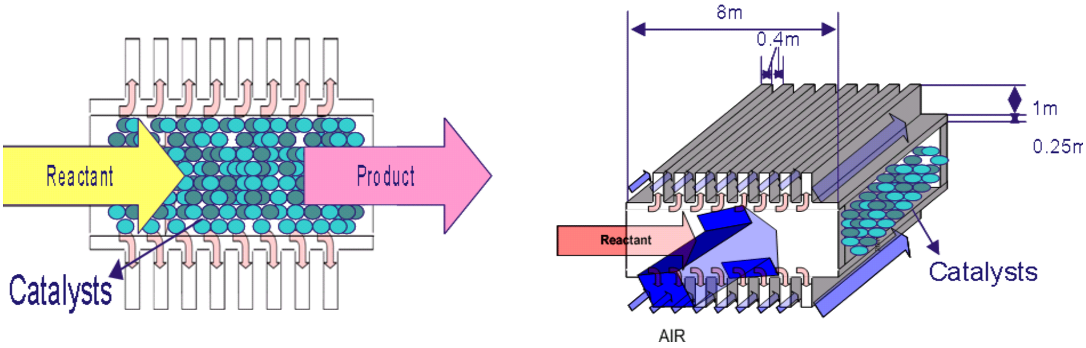

Fig.1.Reactor Design

The temperature of reactor depends on the flow rate and composition of reactant like above diagram. In my model, the temperature at the inlet end of catalytic processor is 450C, and it is increased rapidly to 680C and cooled down to 500C,(Fig.2).

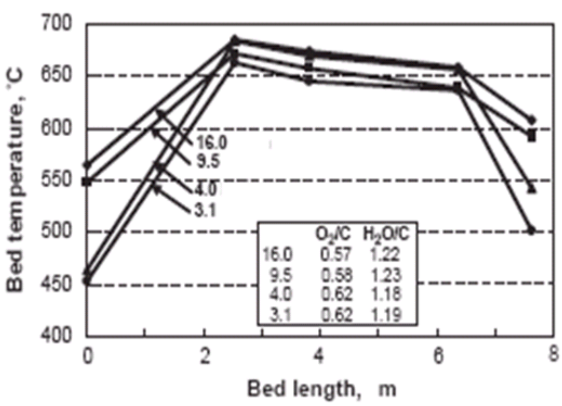

Fig. 2. Temperature profile in the reactor bed (Sheldon H.D. Lee' [3])

2. COMPUTATIONAL MODLING

In order to verify our results obtained using control volume based finite element, computations have been performed on ANSYS. The model in Figure 3 is run on an Intel NT with four processors by ANSYS 5.4. The results and comparisons are summarized in the following. In order to be consistent with what we have for a control volume based finite element model, half size of the(Tet 10node)elements in z- direction is used adjacent to the symmetry line. The half model shown in Figure 3 is generated using total of 13020 nodes and 950 quad elements The wall is designed to be sufficiently thin so that the temperature variations across the thickness of the wall are important.

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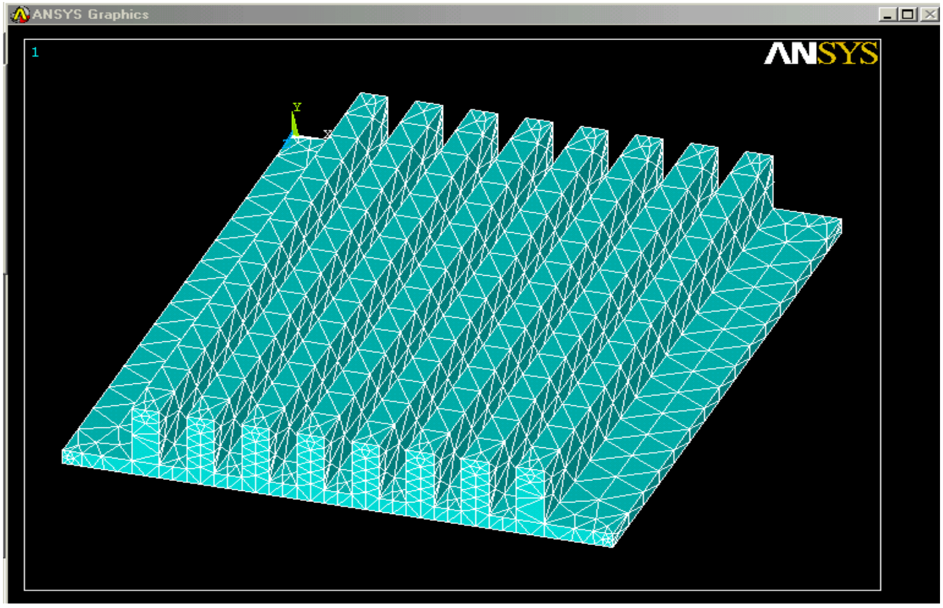


Figure 3

2.1. Boundary condition

The heat transfer in the profile is described according to the equation for steady-state heat conduction in a solid. (with no internal heat sources). The heat transfer within the fin is governed by the stationary heat equation.

$$(k.\nabla T) = 0 \quad \cdots\cdots\cdots\cdots(1)$$

Where k is thermal conductivity, and T is temperature. On the external boundaries of the fin, which face the air, heat convection term is added.

$$n \cdot (-k \cdot \nabla T) = q_0 + h(T_{surr} - T) \quad \text{(z direction)} \quad \cdots\cdots\cdots\cdots.(2)$$

Where n is the normal vector of the boundary, h is the heat transfer coefficient and T_{surr} is the temperature of the surrounding. The term on the right side of the above equation is the Newton's law of cooling. The value for the heat transfer coefficient at the side of reactor is approximated with a 10 $Wm^{-2}K^{-1}$, since the fluid velocity is close to constant and the temperature of the fluid is assumed to decrease only slightly. The ranges of h on the surface of the wall are varied from 10 to 150 $Wm^{-2}K^{-1}$ for forced convection in air. For forced convection, the fluid motion is caused by mechanical means such as pumps and fans. In this system, the heat transfer coefficient is defined as a constant for a convenience of calculation. On the external boundaries of the wall is also governed by below equation.

$$n.(k.\Delta T) = q_0 + h(T_{\inf} - T) + \sigma\varepsilon\left(T_{amb}^4 - T^4\right) \quad \cdots\cdots\cdots\cdots..(3)$$

for Stainless Steel: $\sigma\varepsilon = 5.67 \times 10^{-8} (W/m^2 \cdot K^4) \times 0.25 = 1.4175 \times 10^{-8} W/m^2 \cdot K^4$

for Aluminum: $\sigma\varepsilon = 5.67 \times 10^{-8} \times 0.04 = 2.268 \times 10^{-11} W/m^2 \cdot K^4$

:Emissivity , σ :Stefan-Boltzmann constant, ε where:

1)Material Properties

Material	k[$Wm^{-1}K^{-1}$]	[kgm^{-3}] ρ	[$Jkg^{-1}K^{-1}$] C_p
Steel AISI 4340	44.5	7850	460

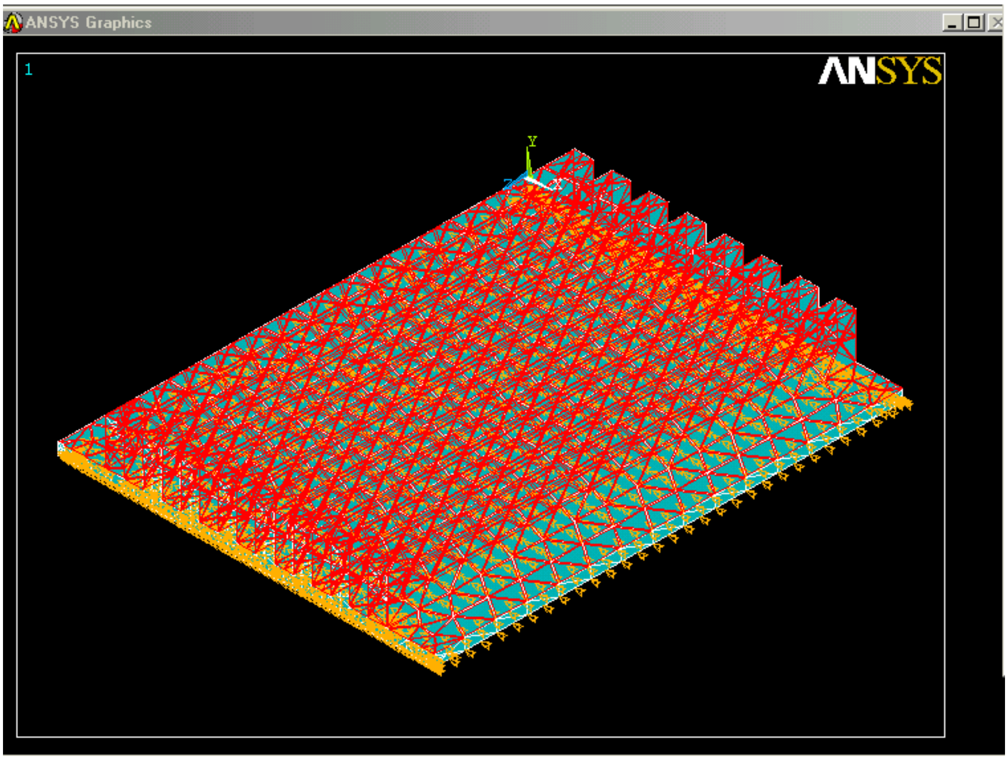


Fig. 4. Reactor wall and boundary Condition

2) Function of Temperature (Boundary condition)

X	0	2.5	3.5	6	7.5
T0_ht(x)(K)	723.15	938.15	923.15	918.15	773.15

3. System Validation

To validate the system, manually was simulated:

$$n\cdot(k\nabla T)=q_0+h(T_{\inf}-T)+const(T_{amb}^4-T^4) \qquad \cdots\cdots\cdots..(4)$$

where T is a function of both x and z, but the dependence on z is more important. A small quantity of heat is lost from the fin at the end and the edges in real system. Some assumptions is needed in validation of the system

1) T is a function of x alone
2) No heat lost from the end or from the edge

$q=h(T-T_{\inf})$, where h = constant, T=T(x)

3) Heat flux at surface is zero
4) Radiation is not concerned in validation.

This equation can be restated;

$$\frac{d^2T}{dx^2}=\frac{h}{kB}(T-T_{\inf}) \qquad \cdots\cdots\cdots\cdots\cdots(5)$$

And the boundary conditions;

(1) $T=Tw \quad x=0$ $\qquad \cdots\cdots\cdots\cdots\cdots..(6a)$

(2) $\frac{dT}{dx}=0 \quad x=L$ $\qquad \cdots\cdots\cdots\cdots\cdots..(6b)$

By introducing following dimensionless quantities

$\theta=\frac{T-T_{\inf}}{T_w-T_{\inf}}$ =dimensionless temperature $\qquad \cdots\cdots\cdots\cdots\cdots..(7)$

$\zeta=\frac{x}{L}$ =dimensionless distance $\qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(8)$

$N=\sqrt{\frac{hL^2}{kB}}$ =dimensionless heat transfer coefficient $\qquad \cdots\cdots\cdots\cdots\cdots\cdots..(9)$

The equation is changed to :

$$\frac{d^2\theta}{d\zeta^2}=N^2\theta \qquad \cdots\cdots\cdots\cdots..(10)$$

with boundary Condition

(1) $\theta=1$ at $\zeta=0$ $\qquad \cdots\cdots\cdots\cdots\cdots\cdots(11a)$

(2) $\frac{d\theta}{d\zeta}=0$ at $\zeta=1$ $\qquad \cdots\cdots\cdots\cdots\cdots(11b)$

Above equation was integrated to give hyperbolic functions. When two integration constants have been determined, The solution is

$$\theta=\frac{\cosh[N(1-\zeta)]}{\cosh(N)} \qquad \cdots\cdots\cdots\cdots\cdots..(12)$$

The system using for validation is the 3rd left fin (Temperature of Wall : 933.15K)

$T_w=933.15K$, $k=44.5W/m\cdot K$, $B=0.2m$, $L=1.25^2m^2$

N=1.33(h = natural convection), 5.13(Forced convection)

5. Results and Discussion

From the result of natural convection (Fig.5.), the heat is dispersed well throughout the reactor wall and the temperature range is from 500 to 938K. All cross-section temperature profiles are converged into around 500K at the end of the fins. The comparison among the temperature profile of surface and insides shows the effect of convection(Fig.6). For the exact observation of heat convection, the convective heat flux h is set to 150 $Wm^{-2}K^{-1}$. Two temperature profiles of insides are similar (the temperature difference between insides of the fin is around 10K), but on the other hand, the temperature at the surface is lower than those of inside (temperature difference between surface and inside is around 40K).

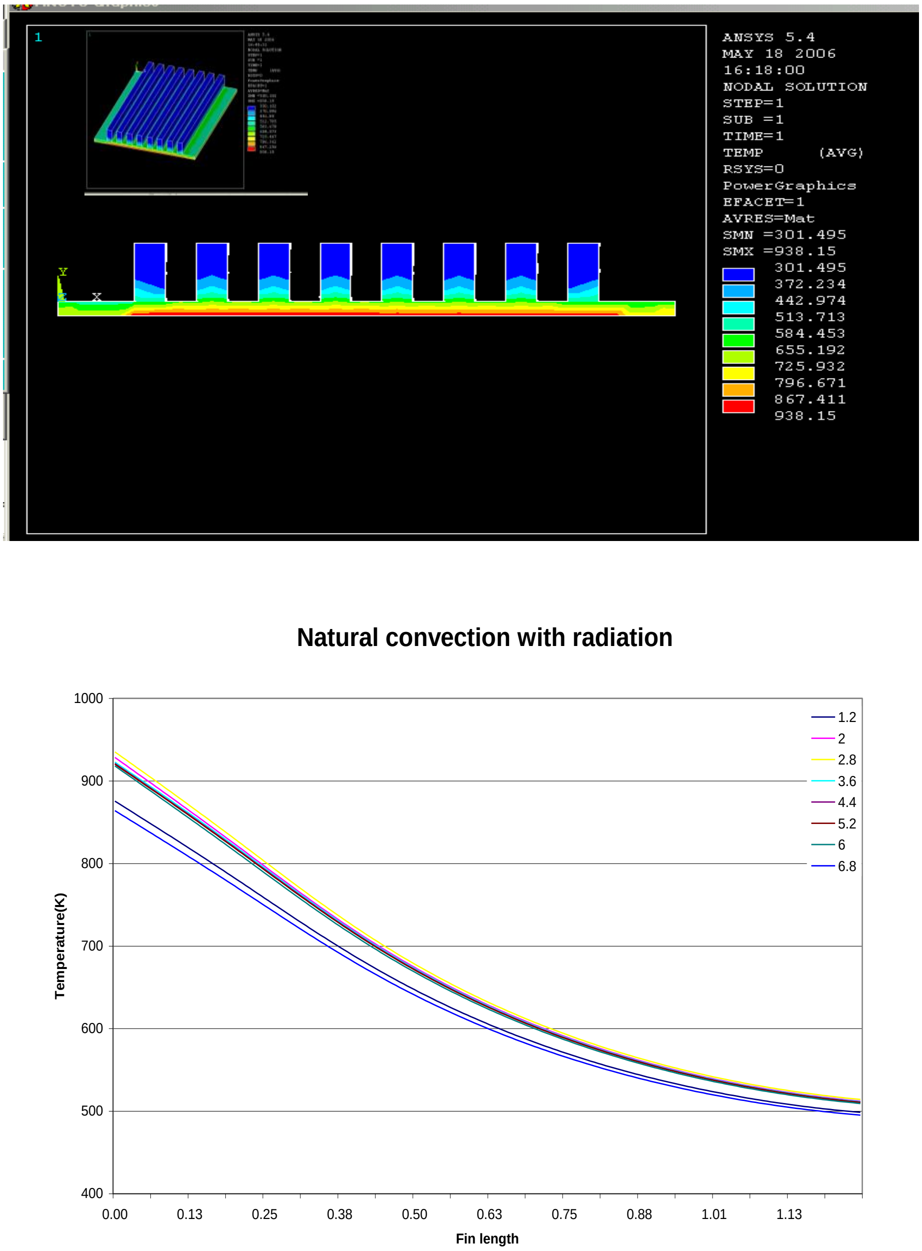


Fig. 5. Temperature profile in the wall

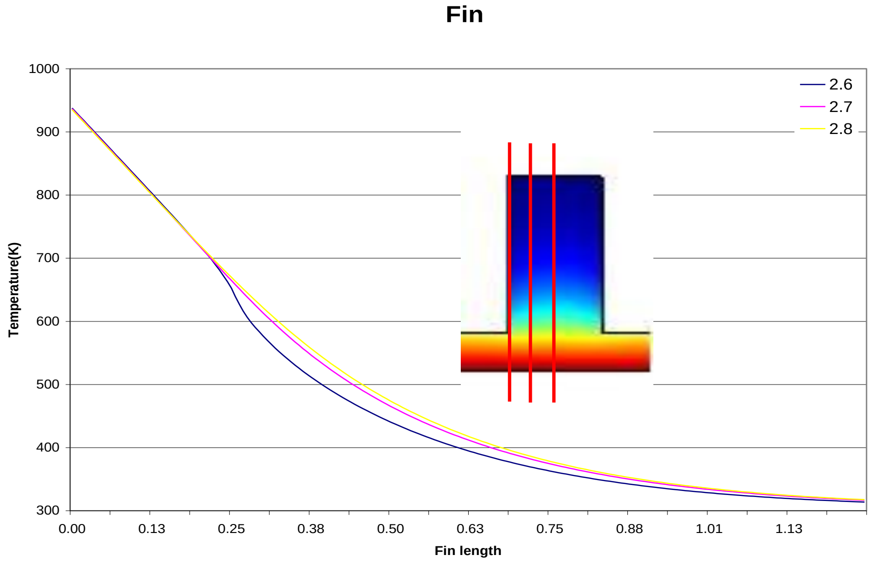


Fig. 6. Temperature profile in a fin

Figure 7 is the results from manual calculation and ANSYS. The calculation of natural convection by hand shows similar result to ANSYS result. However, in forced convection, the manual calculation is lower than that of ANSYS. The main reason is the wall of reactor is assumed to be same with fin and the second assumption "No heat lost from the end or from the edge". Even though the temperature profile of forced convection has differences between ANSYS and Manual calculation, the temperatures at the end of the fin are same.

The Minimum Temperature in the system using ANSYS

Convection Type	Tmin(K)
Forced convection without radiation	307.37
Forced convection with radiation	306.98
Natural convection without radiation	551.075
Natural convection with radiation	489.498

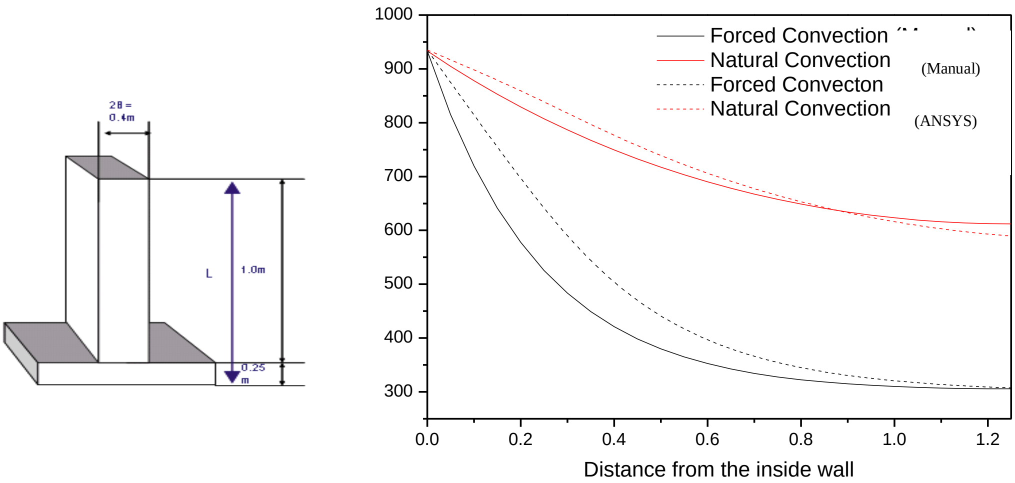


Fig. 7. Comparison between forced convection and natural convection

4. Parametric Study

By changing the convective heat coefficient, radiation coefficient and material properties, parametric studies were performed. Figure 8 shows the temperature profile according to change of the heat coefficient. Temperature at the end of fin is around 610K when the convection term is ignored, but as the heat coefficient is getting increased, the temperature profile is getting decreased.

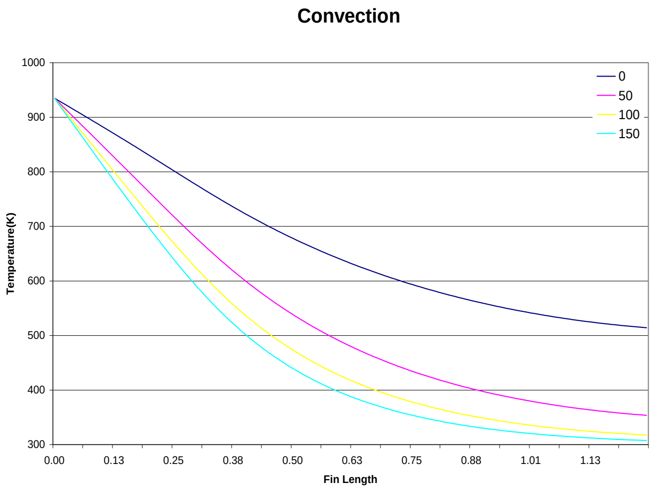


Fig. 8. The effect of convection

Figure 9 displays the temperature profile to confirm the radiation effect. From the graph, the radiation term is important in natural convection system. The temperature profile considering radiation is higher than that considering radiation. At the end of fin, the temperature difference is 75K.

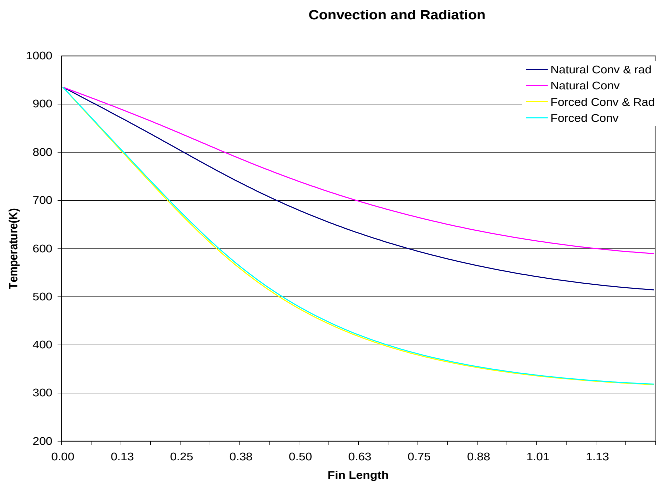
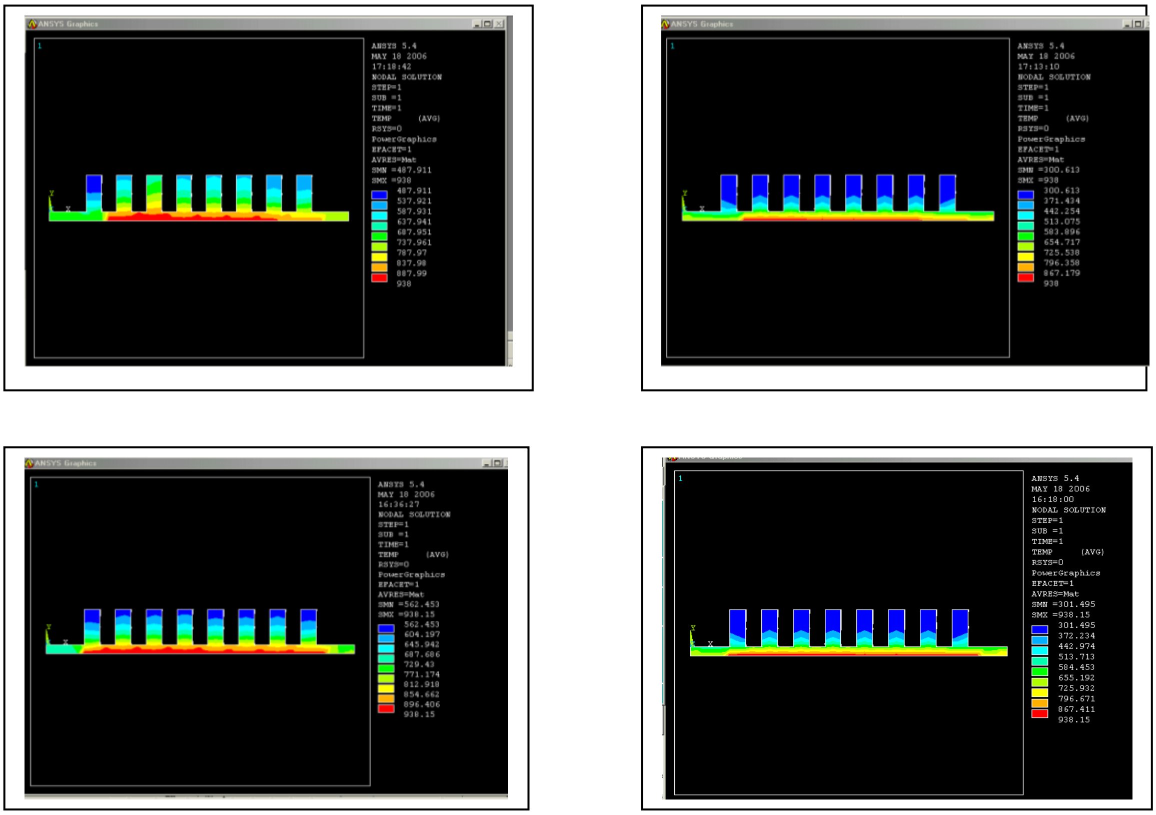


Fig.9. The effect of radiation

However, the temperature profiles of radiation show different aspects. The temperature difference is just 1K, which tells the radiation term did not affect the temperature profile. It means radiation can be ignored in the forced convection system(Figure 9).



Natural convection without radiation Forced convection without radiation

Fig. 10. The effect of convection and radiation

For the effect of material properties, the material is changed from steel AISI 4340 to aluminum. The temperature at the surface of the aluminum wall is 150K higher than that of steel. This is the effect of thermal conductivity's (k) of materials. Thermal conductivity of the aluminum is 200 W/m·K, which is 4 times higher than that of steel (k of steel AISI 4340 is 44.5W/m·K). The temperature of the surface in aluminum is reached to 650K (figure11).

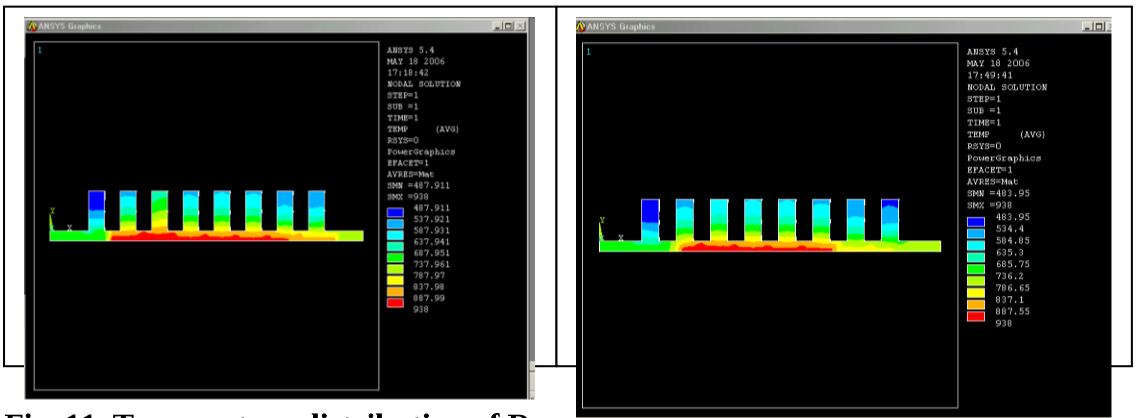
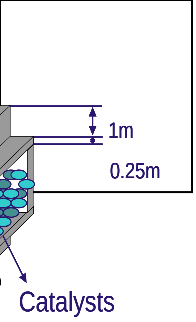


Fig. 11. Temperature distribution of Reactor Wall (L)Stainless Steel, (R)Aluminum



5. Conclusion

Heat exchange with fins was examined and we can find convection term is important factor in calculation of surface temperature. Comparison between solution from ANSYS and direct calculation of ODE indicates that the former might get the more exact estimated value than the latter which needs more assumptions.

Even though consideration of radiation is important in the natural convection system, it can be easily ignored when convection becomes significant term.

6. References

(1) Bird, Stewart, lightfoot, “Transport Phenomena”, John Wiley & Sons, p. 265-309

(2) Welty, Wicks, Wilson, “Fundamentals of Momentum, Heat, and Mass Transfer, 3rd edition”, John Wiley & Sons, p.252-295

(3) Sheldon H.D. Lee et al, Hydrogen from natural gas, International Journal of Hydrogen Energy, 30, 2005, 829-842

(4) Lindon C. Thomas, “Heat Transfer”, Prentice-Hall International, Inc., p.34-256

(5) Erwin Kreyszig, “Advanced Engineering Mathematics, 8th edition”

(6) John H Lienhard, “A Heat Transfer Textbook”, phlogiston press, p.139-266

(7) Paul Kurowkski, “Good Solid Modeling, Bad FEA” , www.Machinedesign.Com/BDE/ cadcam/ bdecad3/bdecad3_4.html

(8) Carnegie Melon University, “Ansys Tutorial”, www.me.cmu.edu/ academics/ courses/ NSF_Edu_Proj/ ThFlEngr_ANSYS/ Default.htm

(9) University of Waterloo, “Sample Input Form for Rectangular Heat Sink”, www.mhtl.uwaterloo.ca/old/ onlinetools/nat_hs/rect_hs/input.html

(10) University of Leicester, “An introduction to FEMLAB: Heat Conduction Problem”, http://www.le.ac.uk/engineering/computing/eg2090/femlab.pdf

(11) Saini, Manish, “Modeling and optimization of air cooled plane fin aluminum heat sinks used in computer cooling”, Thesis (M.S.)--Pennsylvania State University, 2002

(12) Elsworth, “Course Notes and Resources : Mathematical Modeling of Energy and Geo-Environmental Systems”