Mathematical Modeling & Simulation of Effective Heat Energy Loss in Steel Industry

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ABSTRACT
In research paper, the potential to use waste energies from the steel production at B.S.P. Bhilai C.G. investigated. B.S.P is a leading producer of high strength steel, such as slab, bloom, billets, wire, ingots, other steel products every year. The study is based on energy balances in the different production lines. The energy balance are investigated with applying three dimensional mathematical model at different energy flows.

The work concludes that there is a great potential for increasing the use of waste energy at steel plant. Today many of these flows are pure losses that are cooled away or burnt.

The total heat input for the steel production in one year is approximately 38640 MW & output 37128MW from energy calculations it can be shown that the upper theoretical limit when converting the energy into high quality energy such as electricity is produce.

The conclusion is that it is possible to recycle an impressive amount of energy. The technologies for these are briefly are to use duck system over the continuous casting long slab. Flow fluid through it and transfer liquid to vapour. Same vapour strike on turbine and electric energy generate, which is helpful to steel plant, extra facility and comfort purpose or by doing so making it possible for the local power company to produce more electricity.

General Terms
Bhilai Steel Plant, Bhilai, Chattisgarh, India; Thermal conductivity; Specific heat; Electricity Generation; Ansys Software

Keywords
Steel Industry, Heat, Energy, Efficiency, Percentage error.

1. INTRODUCTION
A Heat Energy Mechanisms and Solidification process are simulated for a continuous casting machine and the constructive shape of the liquid pool is predicted considering at different conditions. Heat energy and Solidification model is described for the C.C. of Steel Slabs. The Model has been established on the basis of the technical conditions of the slab caster in the C.C. unit of Bhilai Steel Plant, C.G. India. This model involves 3-dimentional transient energy equation. The governing equation was solved using control volume method and ansys simulation process. The boundary condition of the mold, water spray cooling and air cooling region have been defined. The mathematical model it is able to invent the shell thickness, temperature distribution in the mold and shell, interfacial gap between shell and mold. The modeling results were verified by the measurement slab, billet, bloom, wire, ingot, surface temperature and a reasonable agreement was succeed.

2. EASE OF USE
Inside the Steel Industry a C.C. process set up is shown in fig.1 Different region of cooling in the C.C. machine are shown in fig. Since the heat transfer place and important role in the C.C., it is desirable to have quantitative understanding of the heat flow process which will permit the prediction of the Shell profile and temperature distribution as a casting variables.

2.1 Preamble
In the copper mold heat is transported to the cooling water. Below the mold, in the called secondary cooling zone, cooling is performed by water sprays, by contact with water cooled support rolls, and in the lower part of the machine by radiation.

2.2 Heat transfer in the mold region is con-Trolled by –
The Convection liquid superheat to the shell surface, latent heat evolution, in the mushy zone, heat conduction through the solid shell, the thickness and the other properties of the interface between the shell and the mold, heat conduction through copper mold, and the heat convection to the mold cooling water. The mechanism of heat transfer from the surface of the strand to the cooling water is complex. It involves resistances in the layer of flux or resolidified mold powder, in the air gap, the mold wall, and in the mold water interface. The thermal conductivities of different layers are given in table 1.

3. OUTCOME
In this document, the mathematical model has been established on the basis of technical condition of the slab caster in the C.C. unit of Bhilai Steel Plant. In this model steel heat capacity and steel thermal conductivity were considered as function of steel temperature and chemical composition. Considering this function, the governing equation is a non linear equation. In this study the equation is solved in non linear state. This model is also capable of predicting the temperature distribution, including the solidus and liquidus isothermal which define the sold shell and mushy zone respectively as a function of section size, pouring temperature, steel composition, casting speed, mold length and spray conditions.

3.1 List of Symbols:

d_{air}	Air gap thickness	m
d_{mold}	Copper mold thickness	m
d_{slag}	Slag layer thickness	m
fs	Solid Steel fraction	
h_{rd}	Heat transfer coefficient due to radiation	$w/m^{20}K$
h_{pray}	Heat transfer due to water spray	$Kw/m^{20}C$
hw	Heat transfer coefficient due to water circulation in the mold.	$w/m^{20}K$
H	Total enthalpy	j/kg
H_l	Steel latent enthalpy	j/kg
H_s	Steel sensitive enthalpy	j/kg
k	Steel thermal connectivity	w/m^0K
k_{air}	Air thermal connectivity	w/m^0K
k_{mold}	Copper mold thermal conductivity	w/m^0K
k_{sc}	Oxide scale thermal conductivity created on the surface of strand	w/m^0K
k_{scale}	Oxide scale thermal conductivity in the water channel	w/m^0K
k_{slag}	Mold powder thermal conductivity	w/m^0K
k_{water}	Water thermal conductivity	w/m^0K
L_f	Latent heat of steel	j/kg
N	Slab thickness	m
Q_{water}	Water flow rate in the spray zone	lit/m^2sec
r_{rad}	Thermal resistance due to radiation	Ω
r_{air}	Thermal resistance due to air gap	Ω
r_{mold}	Thermal resistance due to copper mold	Ω
r_{slag}	Thermal resistance due to slag layer	Ω
r_{water}	Thermal resistance due to water circulation channel	Ω
T	Steel temperature	^0C
T_b	Steel temperature on the domain boundary	^0C
T_{water}	Mean water temperature in the mold channel	^0C
W	Slab width	m
v_c	Casting speed	m/s
α	Steel thermal diffusivity	m^2/s
∂_{sc}	Oxide shell thickness	m
Є	Mean surface emissivity	0.8
σ	Stefan-Boltzmann Constant = 5.67×10^{-8}	$w/m^2\,{}^0C^4$
ρ	Steel density	kg/m^3

3.2 Mathematical Modeling

In fig.2 shows the different regions of the C.C. machine and the model considered for physical simulation of the caster. A typical method of modeling the strand thermal condition shown in fig. the mathematical model is applied to slices of strand that start at the meniscus and travel through the machine at the casting steel. The new slices are generated periodically. A sufficient number of slices exist in each condition zone to give an accurate representation of the thermal condition in each zone.

3.2.1 Object

* Conduction can takes place only in the transverse direction.
* Force convective heat flow in the liquid pool is considered by defining an effective liquid thermal conductivity as
$k_{eff} = 7 \times k_l$ 1

* The density of the steel is constant, but specific heat capacity and heat conductivity of steel are function of temperature and chemical composition and therefore not constant.

3.2.2 Model formulation:

The energy conservation equation :

$$\frac{\partial}{\partial t}(\rho H)+\frac{\partial}{\partial x}(\rho u H)+\frac{\partial}{\partial y}(\rho v H)+\frac{\partial}{\partial z}(\rho w H)=\frac{\partial}{\partial x}\left(k_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{eff}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{eff}\frac{\partial T}{\partial z}\right) \quad ....2$$

To simplify the equation, a transformation as $\zeta = z - wt$ is used. Therefore this is:

$$\frac{\partial H_s}{\partial t}=\frac{\partial}{\partial x}\left(\alpha\frac{\partial H_s}{\partial x}\right)+\frac{\partial}{\partial y}\left(\alpha\frac{\partial H_s}{\partial y}\right)-\frac{\partial H_l}{\partial t}+\frac{q^*}{\rho};\quad H=H(x,y,\zeta,t);\quad H=H_s+H_l \quad ....3$$

In order to solve the governing equation, it is necessary to transform the physical domain in to a computational domain. In general sort of transformation is used and leads to a uniformly spaced grid in the computational domain but the point in physical domain may be unequally spaced. The original partial differential equation in transformed from physical coordinates (x,y) to 4

$$\frac{\partial}{\partial t}\left(\frac{H_s}{J}\right)=\frac{\partial}{\partial \xi}\left(\alpha\frac{\partial H_s}{\partial \xi}\frac{\xi_x}{\eta_y}\right)+\frac{\partial}{\partial \eta}\left(\alpha\frac{\partial H_s}{\partial \eta}\frac{\eta_y}{\xi_x}\right)+\frac{S}{J}; \quad ....5$$

$$S=-\frac{\partial H_l}{\partial t};\quad J=\xi_x\eta_y$$

computational coordinates (ξ, η) by applying chain rule of partial derivatives.
In the above equation S is a term for heat source due to metal phase transformation i.e liquid to solid. In order to establish the region of phase change, the latent heat contribution is specified as function of temperature.

Where L_f is the latent heat of the phase change and the liquid fraction (f_l) is calculated – $H_l = f_l \cdot L_f$

$$f_l=\begin{cases}1 & when\ \ T \ge T_{liq}\\ \dfrac{T-T_{sol}}{T_{liq}-T_{sol}} & when\ \ T_{liq} \ge T \ge T_{sol}\\ 0 & when\ \ T \le T_{sol}\end{cases} \quad ....6$$

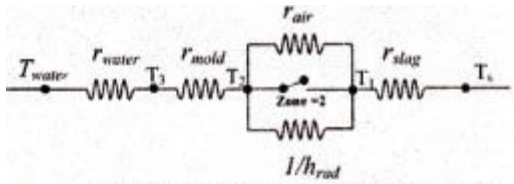
A 2-dimentional Cartesian control volume method, central node (P) with four neighborhood points (E,W,N & S). Here thermal ANSYS software use for calculation of result –

3.2.3 Boundary Condition

After solving the above equation, the boundary condition are needed for different region include the mold, water spray cooling and air cooling. Fig. shows some machine cooling layouts while the technical information belonging to each zone is shown in table 2. A general form of the boundary condition can be expressed through a below equation, in which the heat transfer coefficient, h is estimated for different cooling zones.

$$-k\frac{\partial T}{\partial n}\Big|_b = h(T_b - T_{water}) \quad ....7$$

$$r_{water}=\left(\frac{d_{scale}}{k_{scale}}+\frac{1}{h_w}\right) \quad ....8$$



Thermal resistances existing between the shell surface and water channel in the mold.

The heat transfer coefficient between the water and the side wall of the water channel (h_w) is calculated assuming a turbulent flow through an equivalent diameter pipe D using the imperical of Sleicher and Reusse correlation –

$$h_w=\frac{k_{water}}{D}\left(5+0.015\,\mathrm{Re}^{c_1}\,\mathrm{Pr}^{c_2}\right) \quad ....9$$

$$c_1=0.88-0.24/(4+\mathrm{Pr});\quad c_2=0.333+0.5e^{-0.6\,\mathrm{Pr}} \quad ...10$$

$$r_{mold}=\frac{d_{mold}}{k_{mold}};\quad r_{slag}=\frac{d_{slag}}{k_{slag}};\quad r_{air}=\frac{d_{air}}{k_{air}}; \quad ...11$$

$$d_{slag}=\frac{M_{slag}\times\rho_{steel}}{\rho_{slag}}\times\frac{W\times N}{2(W+N)} \quad ....12$$

$$\Delta l=\lambda\cdot l\cdot\Delta T \quad ....13$$

The heat transfer coefficient due to radiation is calculated by

$$h_{rad}=\varepsilon\sigma\left(T_1^2+T_2^2\right)\left(T_1+T_2\right) \quad ....14$$

Heat energy mechanism in the spray cooling zones below the mold are defined in fig. The heat extraction due to the water spray is a function of the water flux. The relationship between the rate of heat extraction by the water spray and the spray variables has been establishes in the number of experimental studies. One of the most widely relation used by Nozaki's equation below –

$$h_{spray} = 0.3925 \times Q_{water}^{0.55} \times (1 - 0.0075 \times T_{water}) \quad ....15$$

$$h_{eff} = \frac{1}{\frac{\delta_{sc}}{k_{sc}} + \frac{1}{h_{spray}}} \quad ....16$$

$$h_{rad} = \varepsilon\sigma(T_s^2 + T_{am}^2)(T_s + T_{am}) \quad ....17$$

$$x = 0, \quad -k\frac{\partial T}{\partial x} = 0$$
$$y = 0, \quad -k\frac{\partial T}{\partial y} = 0 \quad ....18$$

The high temperature due to of the strand surface and the exposure of the water to the surface, an oxide scale is produced on the surface of the strand. Despite of the low thickness, the scale can have an important role in the heat transfer control, therefore the effective heat transfer coefficient should be considered as –

The symmetrical boundary condition has been considered for mid plane as follows –

It has already mentioned that the cooling of the strand in the lower part of the secondary cooling zone in mainly done by radiation. Therefore the equation of the heat transfer coefficient is given as follows, besides the radiation heat transfer is also achieved by natural convection, but this part is rather small and can be neglected in comparism of radiation cooling.

Equilibrium lever rule calculation are performed on a Fe-C phase diagram in order to calculate steel phase fraction. By this means, phase field lines are specified as simple linear function of carban equivalent content.

For a 0.16%C, 1.3Mn, 0.05%Cr, 0.03%Mo, 0.5%Si and 0.01%Ti plane carbon steel, the carbon equivalent percentage calculated as 0.135 and also the equilibrium phase diagram model calculates T liquid = 1528^0C, T solid = 1494^0C. The solid fraction temperature in the mushy zone obtained from the model.

Steel conductivity, K_{steel}	f_l x k_{liquid} + (1-f_l) x k_{solid}	w/m^{0}K
Carbon equivalent content,	0.132	pct
Steel density, ρ	7500	kg/m^3
Steel emissivity , Є	0.8	
Mold copper plate thickness	0.043 x 0.030	m x m
Total mold name	0.704	m
Mold copper plates width	2.220 x 0.215	m x m
Mod conductivity, k_{mold}	39	w/m^{0}K
Mold powder conductivity, k_{slag}	1.27	w/m^{0}K
Air conductivity, k_{air}	0.083	w/m^{0}K
Mold powder density, ρ_{slag}	0.653	kg/m^3
Mold powder consumption, rate, m_{slag}	0.8	Kg/ton steel
Casting speed, Vc	0.0167	m/sec
Pour temperature, T_{in}	1546	^{0}C
Liquius Temperature, T_{liquid}	1528.6	^{0}C
Solidius Temperature, T_{sol}	1494	^{0}C
Slab geometry, W x N	M1	m x m
	M2	m x m
	M3	m x m
	M4	m x m
	Bloom1	l x b x m
	Bloom2	l x b x m
	Billet 1	l x b x m
	Billet 2	l x b x m
	Wire 1	d
	Wire 2	D
	Ingot	l x b x m
Scale conductivity on the surface of the slab, K_{sc}	0.5	w/m^{0}K
Scale conductivity of the surface of the mold, K_{scale}	1.0	w/m^{0}K
Scale thickness of the surface of the mold	0.00001	m
Average cooling water temperature in mold	28	^{0}C
Water flow rate entering the mold small plate	0.0061	m^3/Sec
Water flow rater entering the mold large plate	0.0553	m^3/Sec
Latent heat of the steel phase change, L_f	272140	J/kg
Water conductivity, K_{water}	0.615	w/m^{0}K
Solid steel conductivity, K_{solid}	33.0	w/m^{0}K
Effective molten steel conductivity, K_{liquid}	7 x 43.0	w/m^{0}K
Scale thickness on the surface of the slab, ∂_{sc}	0.001	m
Steel specific heat capacity, C_P	C_p = 456 + 0.376 x T(^{0}C) T<500	J/kg^{0}K
	C_p = 268+ 0.836 x T(^{0}C) 500<T<700	
	C_p = 1431 700<T<750	
	C_p = 3849 – 3.766 x T(^{0}C) 750<T<850	
	C_p = 648 850<=T<1100	
	C_p = 268+ 0.334 x T(^{0}C) 1100<=T<T_{sol}	
	C_p = 772 T_{sol}<= T<T_{liquid}	
	C_p = 787 T> = T_{liquid}	
Steel conductivity, K_{steel}		

3.2.4 Title and Authors

Mahendra Shivaji Dhande, Lecturer in Mechanical Engineering Dept. , Priyadarshani Institute of Engineering & Technology, Nagpur (M.S.) India. More than 10 year teaching and administration experience and published some international papers.

Dr. S. S. Khandare, principal at Bapurao Deshmukh College of Engineering, Sevagram, Wardha (M.S.), India. Professor has 30 years teaching and administration experience, above 18 books published and number of international papers.

3.2.5 Results and conclusions

Errors in heat loss in C.C. Process (Steel Melting Shop 2) and (Steel Melting Shop 1) also in maintenance equipment –

Solution –

Input heat energy required for solidification purpose, but at the same time loss of radiated heat energy collect and reutilized to run small steam power plant.

Therefore for calculation purpose need only dry coal. For April 2002 month dry coal consumption m_f = 280316 x 10^3/30 days = 389327.78kg/h

Therefore input heat energy supplied

Q = m_f x CV

Q = 389327.78 kg/h x 30400kj/kg

Q(i/p) = 3287656.8 kj/sec or kw

Output in the month of April 2002

Table 2

$Q_{conduction}$	$Q_{radiation}$	$Q_{convection}$
Sheet 1 to 5	Sheet 1 to 5	Sheet 1 to 5
Total = 19819	Total = 81457	Total = 861022.92 x G (Effect to Thermal conductivity)

Adding output = $Q_{conduction}$ + $Q_{radiation}$ + $Q_{convection}$

$QTotal_{(o/p)}$ = 3114856.2

Efficiency of Steel Plant = Output/input

= 0.9474 (or) 94.7439%

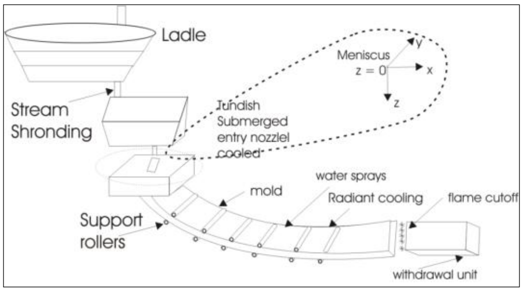
%age error

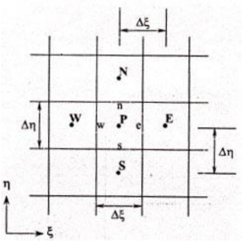
= (Input – Output) x 100/Output = 5.5476262%

Conclusion : In Energy Loss -

* transportation of ingot one shop to another shop,
* Transportation of ladle
* Slag layer is wastage product over the molten solution
* Heat energy loss in continuous casting
* Molten metal float through land channel
* Heat energy radiated at pouring in time

4. Figure & Tables





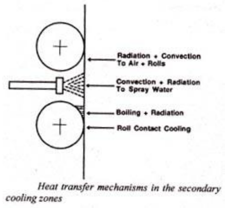


Table 1 – Heat Loss
K = 301 and h = 8468.3086

Size(m)	Parameter	$Q_{conduction}$(kw)	$Q_{convection}$(kw)	$Q_{radiation}$(kw)
0.2 x 1.5	m1(slab)	1.571	44.203	3.447
0.32 x 1.2	m2(slab)	2.513	70.725	5.515
0.25 x 1.5	m3(slab)	1.964	55.253	4.308
0.2 x 1.3	m4(slab)	1.361	38.309	2.987
0.31 x 0.34	Bloom 1	0.552	15.530	1.211
0.32 x 0.32	Bloom 2	0.536	15.088	1.776
0.28 x 0.28	Bloom 3	0.410	11.551	0.900
0.26 x 0.34	Bloom 4	0.462	13.025	1.015
0.26 x 0.30	Bloom 5	0.408	11.492	0.078
0.090 x 0.090	Billet 1	0.042	1.193	0.093
0.1 x 0.1	Billet 2	0.523	1.473	0.114
0.11 x 0.11	Billet 3	0.063	1.782	0.139
0.15 x 0.15	Billet 4	0.117	3.315	0.258
0.105 x 0.105	Billet 5	0.057	1.624	0.126
0.128 x 0.128	Billet 6	0.085	2.414	0.188
π x 2.75 x 2.75	Wire 1	124.368	3498.864	272.855
π x 3 x 3	Wire 2	148.008	4163.937	324.720
π x 3.5 x 3.5	Wire 3	201.456	5667.582	441.980
π x 4 x 4	Wire 4	263.126	7402.556	577.280
π x 5 x 5	Wire 5	411.135	11566.494	902.00
π x 6 x 6	Wire 6	592.035	16655.751	1298.881
0.060 x 0.060	Ingot	0.0188	0.530	0.014
Total		1750.8108	49242.691	3839.312

Table 2
Cooling zones variables

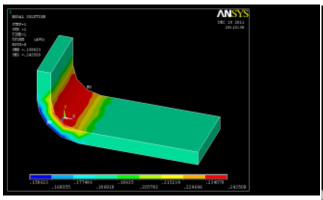
. of ne	Length of zone (m)	Segments	No. of spray Nozzles	Water flow rate (m^3/s)	No. of rolls in zones	Roll radius (m)
1	0.439	-	-	-	-	-
2	0.220	-	-	-	-	-
3	0.303	-	30	0.0039	-	-
4	0.925	0	38	0.0049	5	0.140
5	1.470	0	38	0.0048	6	0.200
6	1.475	1	10	0.0048	5	0.25
7	1.725	2	10	0.0039	5	0.30
8	1.725	3	10	0.0037	5	0.30
9	3.950	4	20	0.0056	10	0.35
0	5.200	Roll 36-48	22	0.0064	11	0.38
1	9.400	Roll 47-64	-	Air cooling	16	0.44

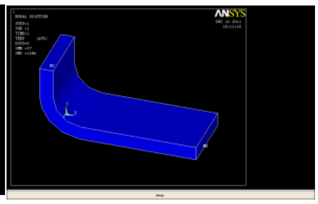
Table 3 –
Comparism of Thermal Conductivity of materials present in the C.C. mold

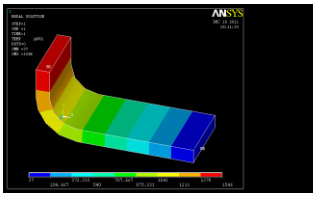
Material	Temperature (^{0}C)	Thermal conductivity (w/m^0K)
Water	25	0.62
Casting flux	1050-1350	0.5 to 1.2
Copper	30 to 130	385
Steel St.37	1200	29

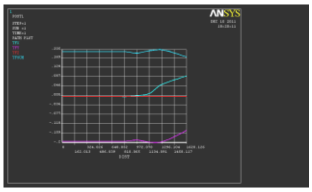
4.1 Representation of C.C. Process

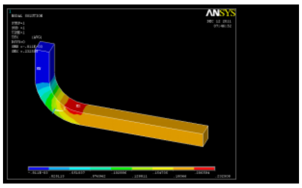
4.2 Simulation of C.C. Process (Conduction, Convection, Radiation)

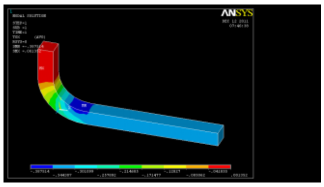


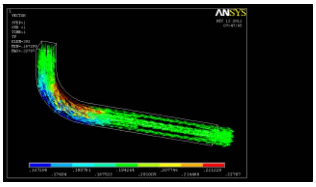


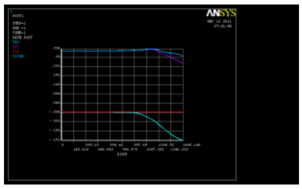


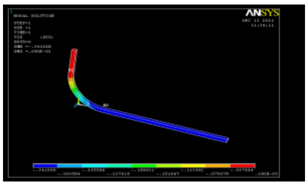


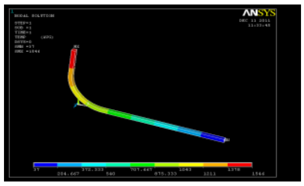


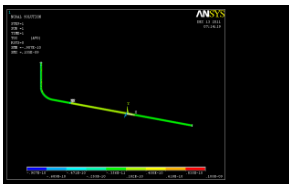


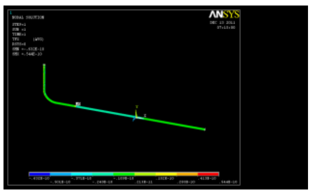


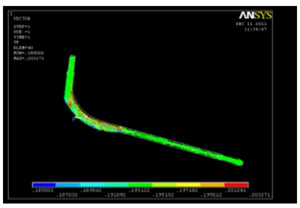


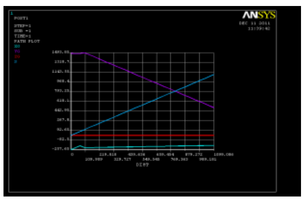


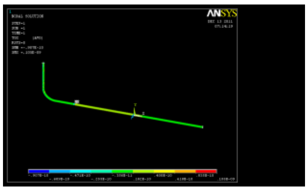
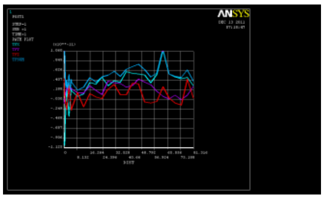
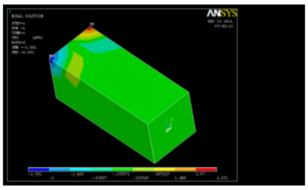
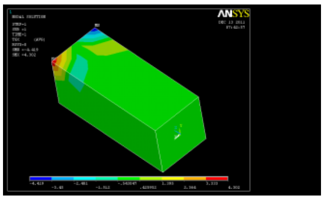
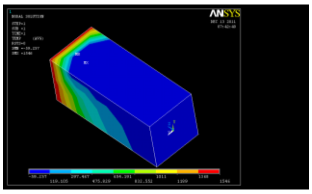
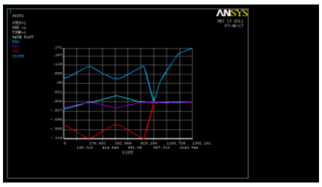










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