Induction Heating

(Electromagnetic + Thermal analysis in Flux)

2017.10.31

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Altair

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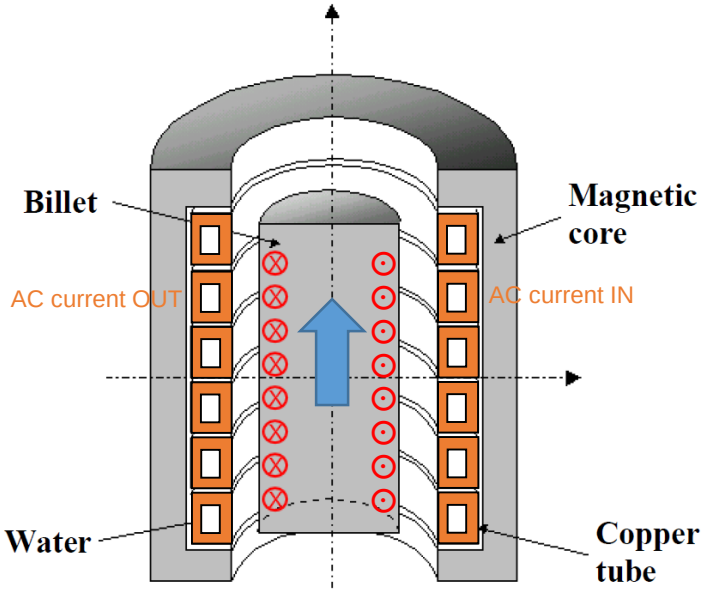
How the induction heating works



① AC current 에 의해 BILLET에 시간에 따라 변하는 자계(⬆)가 발생한다.

② Faraday's law에 의해 BILLET에 전압이 유기되고 eddy current 가 흐르게 된다.

$$emf = -\frac{d\lambda}{dt} \text{ [V]} \quad (\text{ t : time, } \lambda \text{ : Linked flux })$$

③ Eddy current 가 흐름으로서 Joule loss 가 발생한다. 즉, 열이 발생한다.

$$\text{Jouleloss or Thermal energy} = I^2 \cdot R \text{ [W]}$$

입력 소스의 주파수가 10kHz 이상으로 eddy current 가 크게 발생하며 열 또한 많이 발생한다.

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Case 1 : Magnetic
- Finding the optimal frequency of input source

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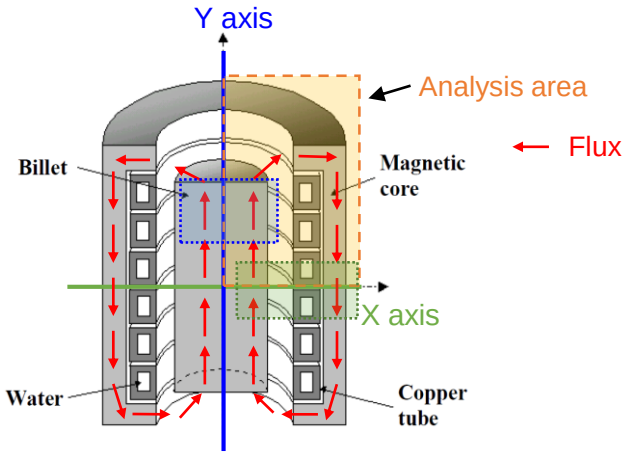
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 1. Geometry

1. Creation of symmetry to simplify the geometry construction
   - Symmetry versus X axis, Physical aspects ; Normal magnetic fields
   - Symmetry versus Y axis, Physical aspects ; Tangent magnetic fields

   ➡ It is possible to build more mesh and save more analysis time than the full model



Choosing physical aspects

- The flux and axis are perpendicular (Green box) ➡ Normal magnetic fields option
- The flux and axis are parallel (Blue box) ➡ Tangent magnetic fields option

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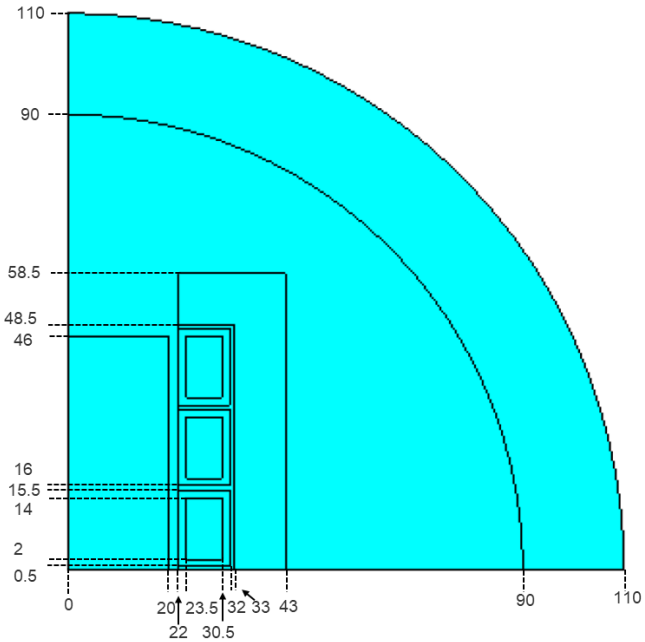
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 1. Geometry

2. Building the model



Infinite box
- inner radius : 90
- outer radius : 110

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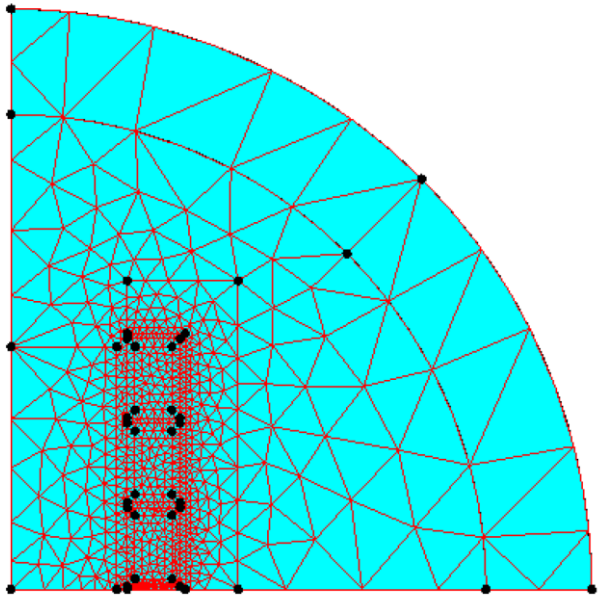
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 2. Mesh

- Building the default mesh



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Case 1 : Magnetic - Finding the optimal frequency of input source

Step 3. Define problem

- Problem : Steady state AC magnetic 2D
- Frequency : *50 kHz
- 2D domain type : Axisymmetric

Step 4. Physical parameter

Parameter name	Type of I/O parameter	Value
FREQUENCY	Parameter controlled via a scenario	50,000
V_SOURCE	Parameter controlled via a scenario	120

* 50 kHz ⇨ FREQUENCY

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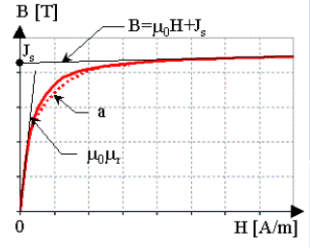
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 5. Material

Name	B(H)	J(E)
STEEL_1	Isotropic analytic saturation+knee adjustment (arctg,3 coef.) Initial relative permeability(ur) : 600 Saturation magnetization(Js) [T] : 2.0 Knee adjustment coefficient(α): 0.4	Isotropic resistivity Resistivity(R) [Ohm.m] : 2.5e-7
COPPER	Linear isotropic Relative permeability(ur) : 1.0	Isotropic resistivity Resistivity(R) [Ohm.m] : 2.0e-8
FERRITE	Isotropic analytic saturation+knee adjustment (arctg,3 coef.) Initial relative permeability(ur) : 200 Saturation magnetization(Js) [T] : 0.4 Knee adjustment coefficient(α): 0.4	No setting



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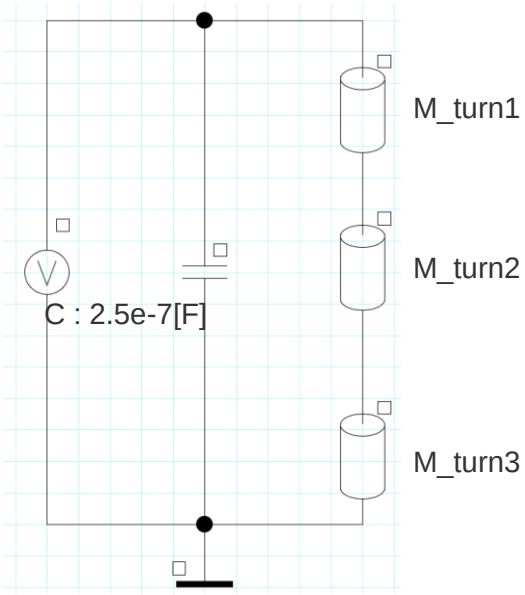
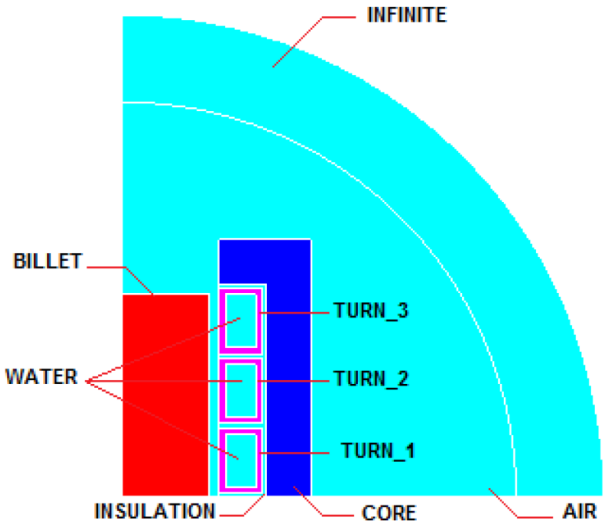
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 6. Circuit

Voltage : V_SOURCE [V]
Phase : 0





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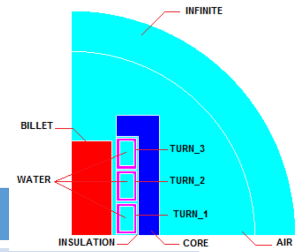
Case 1 : Magnetic - Finding the optimal frequency of input source



Step 7. Face region

Name	Color	Material	Magnetic definition		
			Type	Type of the conductor	Associated solid conductor
AIR	Turquoise	-	Air or vacuum region	-	-
BILLET	Red	STEEL_1	Solid conductor region	No circuit	-
CORE	Cyan	FERRITE	Magnetic non conducting region	-	-
INSULATION	Turquoise	-	Air or vacuum region	-	-
TURN_1	Magenta	COPPER	Solid conductor region	Circuit	M_TURN1
TURN_2	Magenta	COPPER	Solid conductor region	Circuit	M_TURN2
TURN_3	Magenta	COPPER	Solid conductor region	Circuit	M_TURN3
WATER	Turquoise	-	Air or vacuum region	-	-
INFINITE	Turquoise	-	Air or vacuum region	-	-

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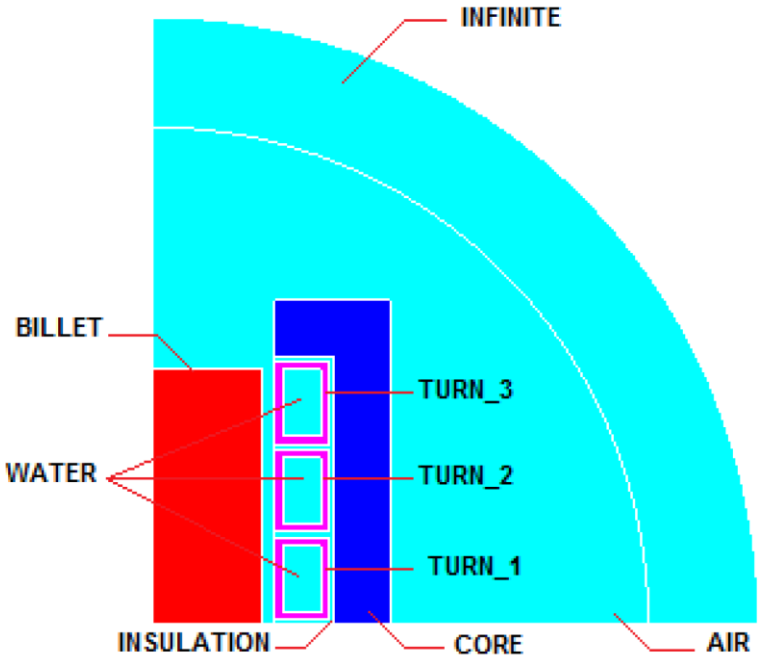
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 7. Face region



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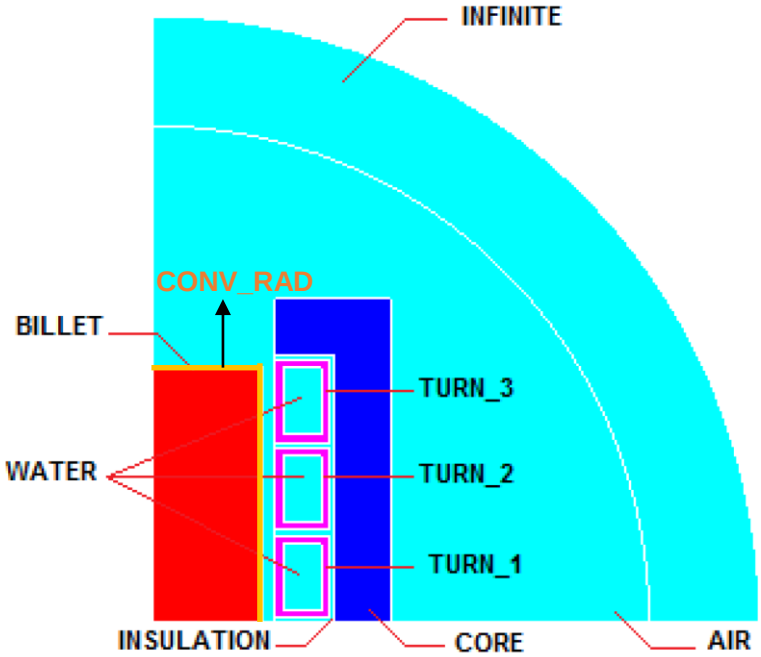
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 8. Line region



Line region

- Name : CONV_RAD
- Type : Inactive region

- Line region CONV_RAD는 공기와 BILLET의 경계로 이 경계 위에서의 계산이 모호하다. 이로 인해 잘못된 값이 계산 되기 쉬운 부분이다.

- 따라서 이 경계를 Inactive region으로 설정하므로서 해결할 수 있다.

- 일반적으로, 별도의 설정이 필요 없으나 중요한 부분의 경우 이와 같이 설정해주는 것이 좋다.

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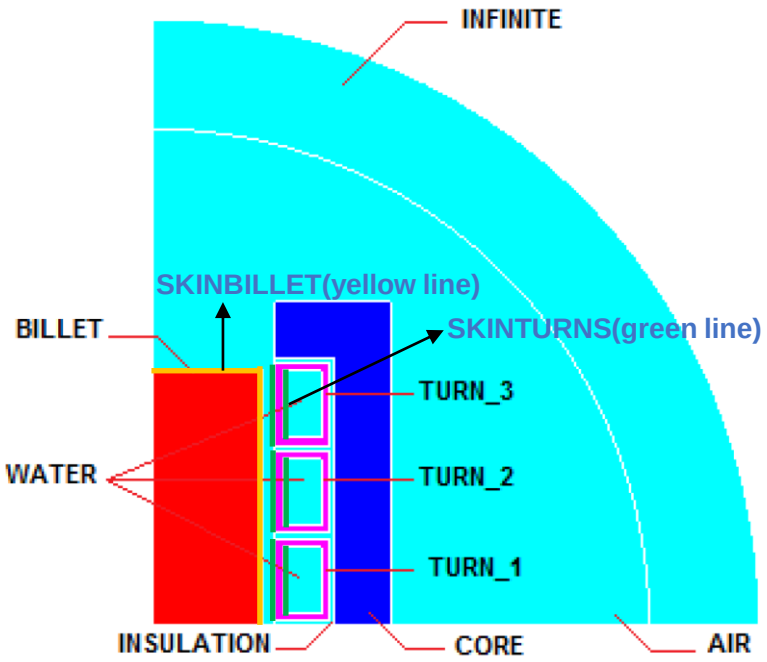
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 9. Skin effect mesh



- Eddy current 는 BILLET 의 가장자리에 흐르고 그 깊이는 아래와 같이 계산 한다.

$$depth = \sqrt{\frac{2\rho}{2\pi f \mu}}$$ (ρ : resistivity, f : frequency, μ : permeability)

- **Project > Macro > Load > MeshSkinEffectFaceRegion.PFM**

Name	Number of layers	Skin Depth (m)
SKINBILLET	2	4.59e-5
SKINTURNS	2	3.18e-4

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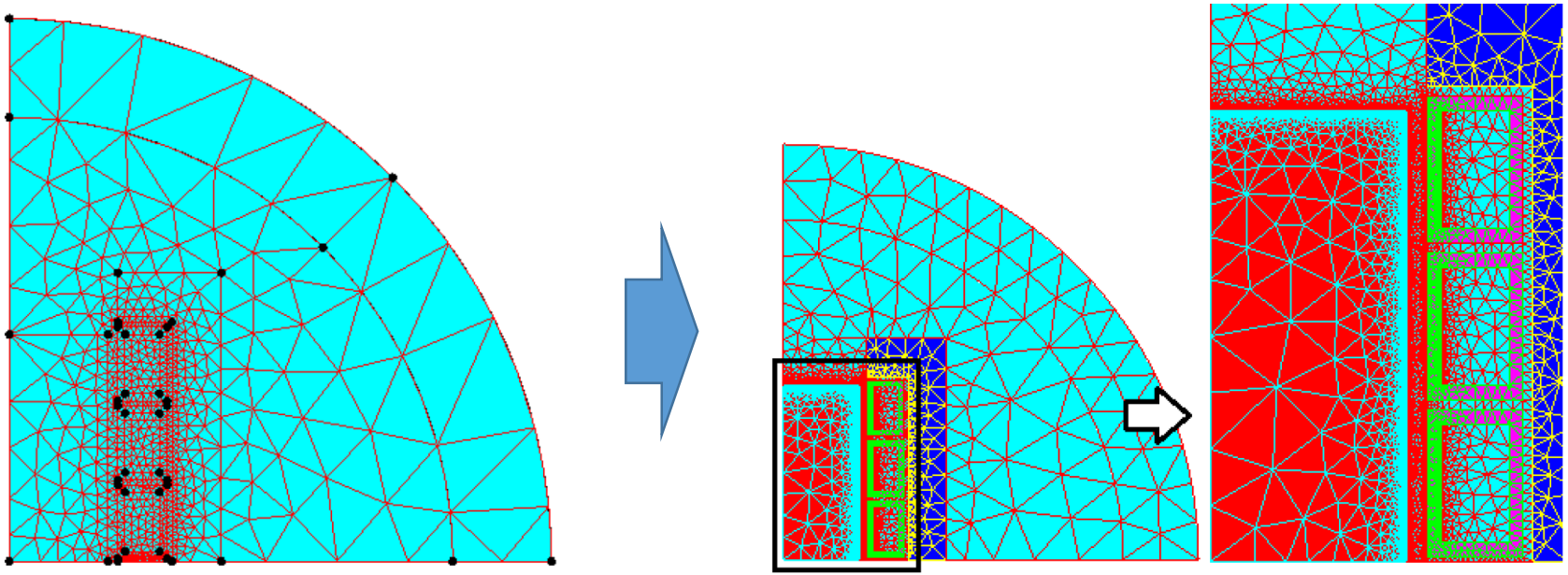
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 9. Skin effect mesh



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Case 1 : Magnetic - Finding the optimal frequency of input source

Step 10. Solving (Scenario)

- Parametric analysis setting

Name	Lower limit	Higher limit	Steps
FREQUENCY	10,000 [Hz]	100,000 [Hz]	Step number(lin) : 10
~~V_SOURCE~~	~~80 [V]~~	~~160 [V]~~	~~List of steps : 100, 110, 120, 130, 140~~

V_SOURCE : 120 [V]

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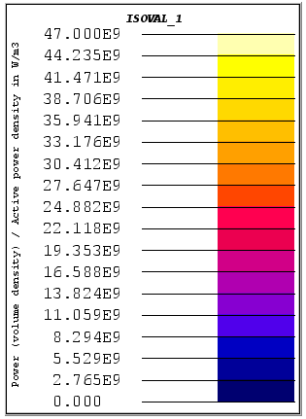
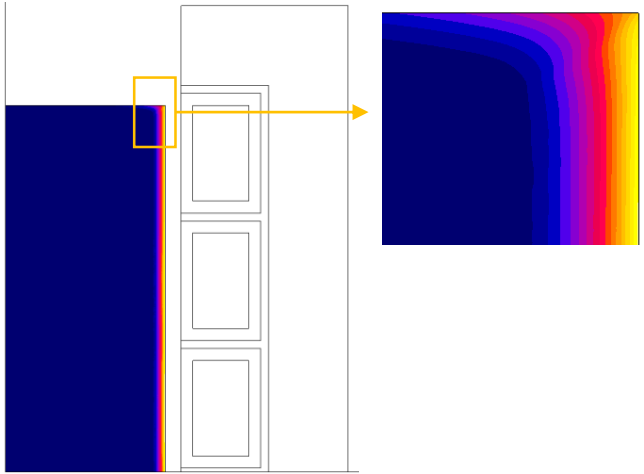
Case 1 : Magnetic - Finding the optimal frequency of input source

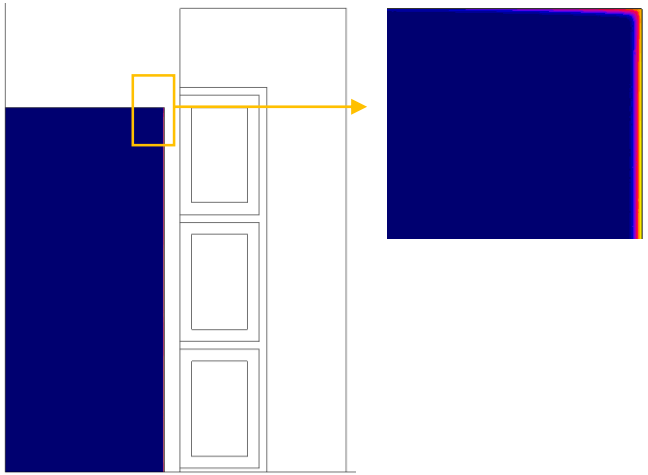
Step 11. Post process

- Joule loss field





V_source : 10kHz, 120V



V_source : 100kHz, 120V

주파수가 높을수록 skin depth가 얇아져 표면에 손실이 집중 된다.

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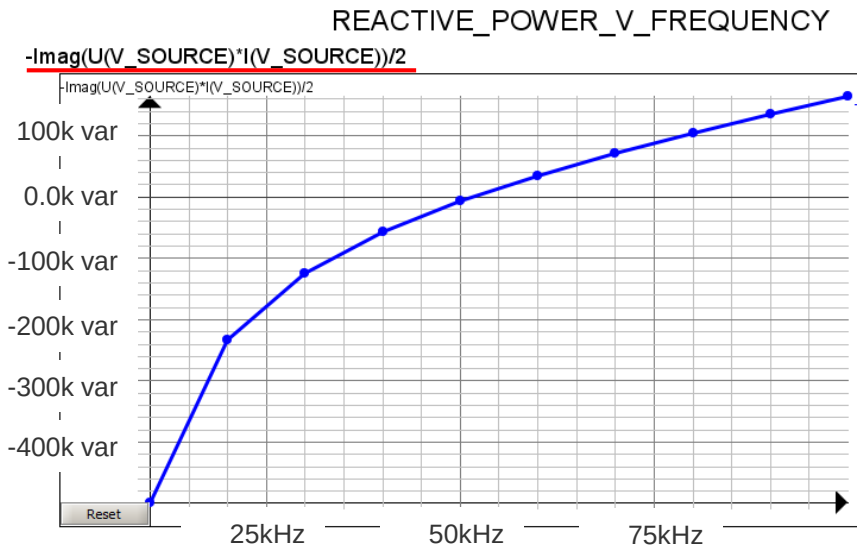
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 11. Post process

- Finding the optimal frequency of input power



- 열에 기여하는 power 는 active power[W] 로 complex power[VA] 의 실수부이다.
- Induction heater 에는 L과 C 성분이 존재하기 때문에 reactive power[var] 가 존재한다.
- Reactive power 가 0 이 되면 V_SOURCE 모든 power가 active power가 된다는 의미이므로 열효율이 증가한다.
- 이 때의 주파수를 공진 주파수라고 하고, 이 case의 경우 50.7 [kHz] 가 공진주파수이다.

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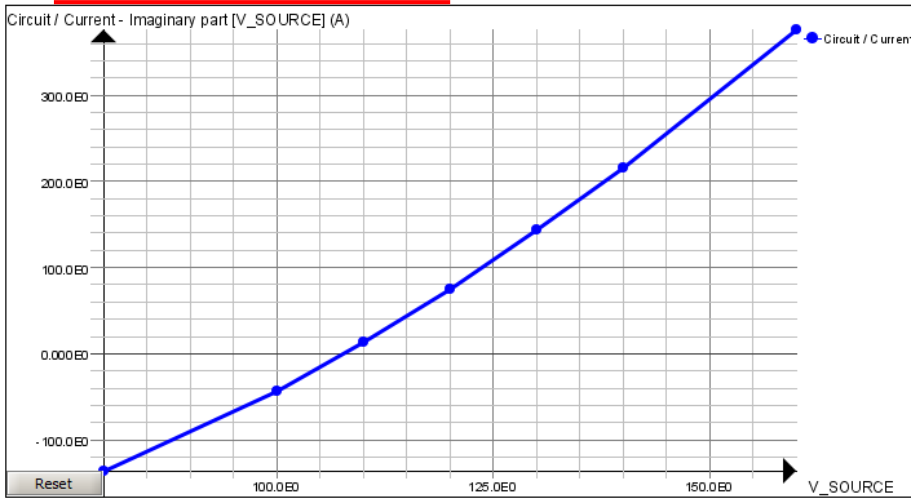
Case 1 : Magnetic - Finding the optimal frequency of input source

Step 11. Post process

- Sign of the imaginary current

IMAGCURRENT_V_VOLTAGE

Circuit / Current - Imaginary part [V_SOURCE]



- BILLET 과 CORE 가 비선형 물성으로 전압에 따라 L 값이 변화하여 전류의 허수부가 변한다.
- L이 커지면 전류의 허수부가 음의 값을 갖는데 비선형 물성 재료의 경우 전압이 커지면 포화가 되어 L 값이 작아지므로 전압이 일정 값 이상으로 증가하면 전류의 허수부가 양의 값으로 전환된다.

$$I = \frac{V}{Z'} = \frac{V}{j(wL - \frac{1}{wC})} = j\frac{-V}{(wL - \frac{1}{wC})}$$

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Case 2 : Magnetic coupled thermal – temperature independent

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Case 2 : Magnetic coupled thermal – temperature independent

Description

BILLET의 물성에 열 특성 상수(열전도율과 열용량)를 추가하여 Joule loss로 부터 발생한 열이 BILLET에서 어떻게 전달 되는지를 알 수 있다.

Step 1. Edit the physical application

- Problem : Steady state AC magnetic coupled with Transient Thermal 2D application
- Frequency : 50 kHz
- 2D domain type : Axisymmetric
- Temperature unit : CELSIUS_DEGREE
- Transient initialization : With zero initial solution (variables set to 0)

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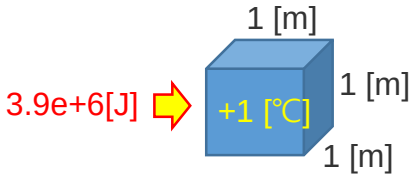
Case 2 : Magnetic coupled thermal – temperature independent

Step 2. Edit the material properties of BILLET(STEEL_1)

k(T)
- Isotropic, constant
- Thermal conductivity : 47 [$W \cdot m^{-1} \cdot ℃^{-1}$]

RCP(T)
- Constant
- Volumetric heat capacity : 3.9e+6 [$J \cdot m^{-3} \cdot ℃^{-1}$]



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Case 2 : Magnetic coupled thermal – temperature independent

Step 3. Input the thermal definition on the face regions

Name	Thermal definition	
	Type	Possible thermal source
BILLET	Thermal conducting region with heat thermal source	Heat computed by Joule effects during electromagnetic solving process
AIR, CORE, INSULATION TURN_1, TURN_2, TURN_3 WATER, INFINITE	Inactive region	-

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Case 2 : Magnetic coupled thermal – temperature independent

Step 4. Input the thermal definition on the line regions

Name	Radiation				
	Type	Definition	ε	α	Temperature [℃]
BILLET	Radiation to infinite	I/O parameters	0.5	0.5	20

Name	Convection		
	Definition	Convection coefficient h	Temperature at infinite [℃]
BILLET	I/O parameters	20	20

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Case 2 : Magnetic coupled thermal – temperature independent

Step 5. Solving (Scenario)

Name	Parameter control							
	Controlled Parameter	Interval						
		Lower limit (s)	Higher limit (s)	Variation Method	Initial step value (s)	Min step value (s)	Max step value (s)
SCENARIO_1	TIME	0.0	0.05	Adaptative step	0.005	5.0e-4	0.005
		0.05	4	Adaptative step	0.005	5.0e-4	0.05

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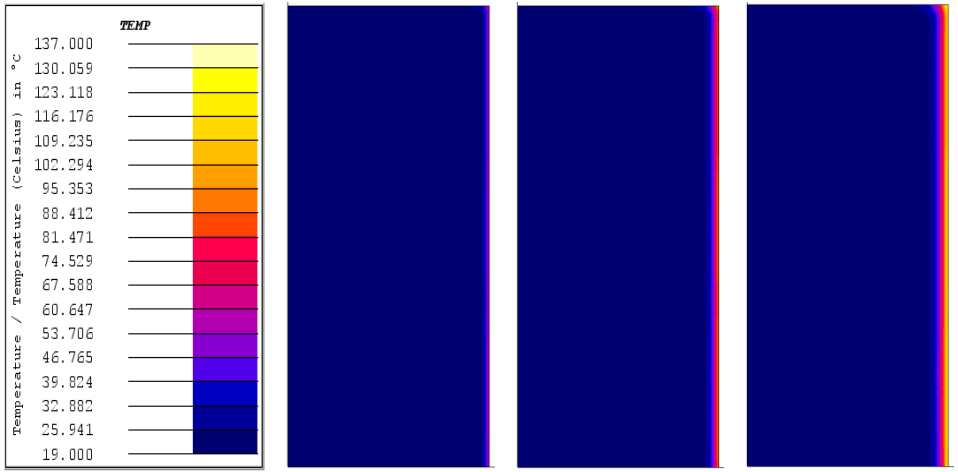
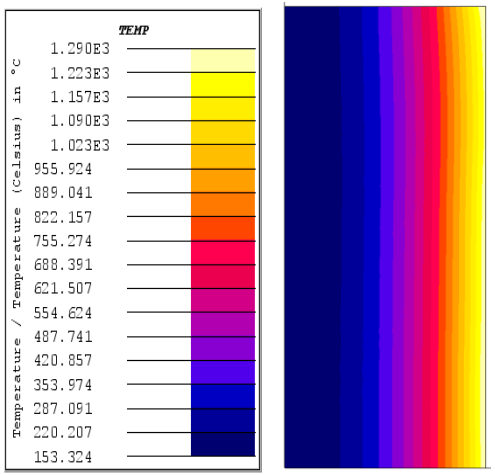
Case 2 : Magnetic coupled thermal – temperature independent

Step 6. Post process

- Temperature distribution



0.01 [s] 0.025 [s] 0.045 [s]



4.0 [s]

✓ BILLET 내에서 전달 되는 것을 알 수 있다.
✓ 열원이 계속 열을 공급하고 있으므로 4.0 [s] 까지 지속적으로 온도가 증가한다.

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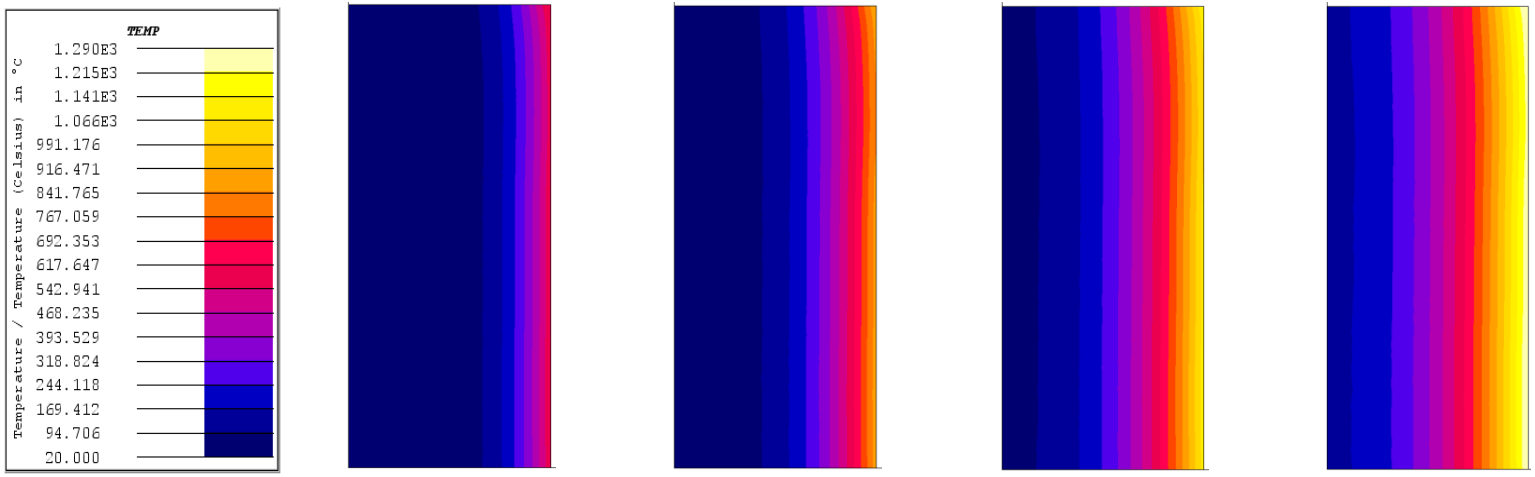
Case 2 : Magnetic coupled thermal – temperature independent

Step 6. Post process

- Temperature distribution



1.0 [s] 2.0 [s] 3.0 [s] 4.0 [s]

✓ BILLET 내에서 전달 되는 것을 알 수 있다.
✓ 열원이 계속 열을 공급하고 있으므로 4.0 [s] 까지 지속적으로 온도가 증가한다.

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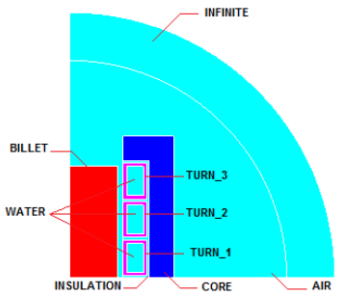
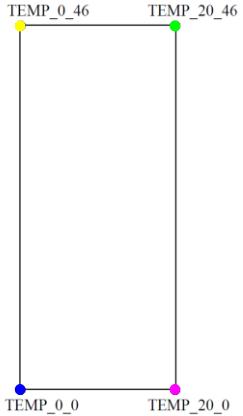
Case 2 : Magnetic coupled thermal – temperature independent

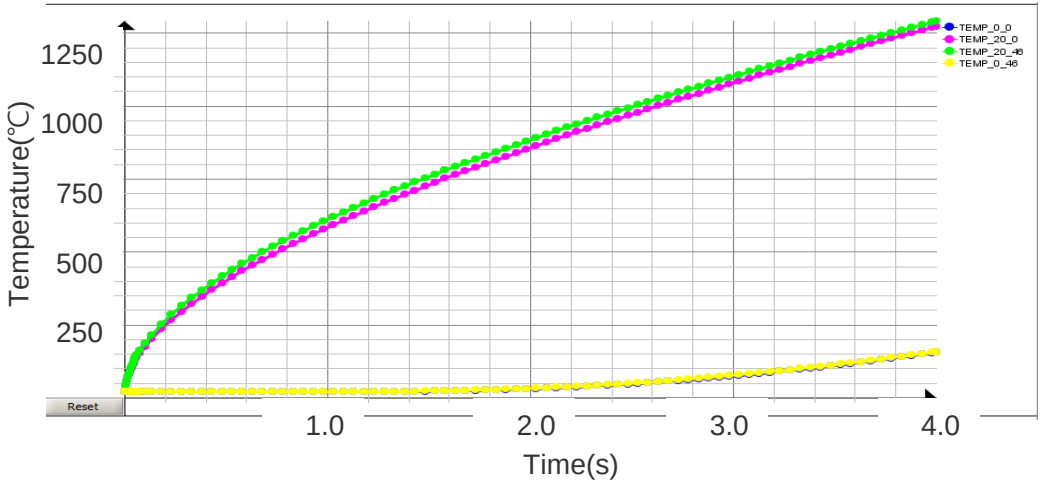
Step 6. Post process

- Temperature at the points





<BILLET>



- ✓ 점(20, 0)과 (20, 46) 이 코일과 가까우므로 다른 두 점에 비해 온도가 높고, 점(20, 46)은 위쪽에 코어가 가깝게 있기 때문에 eddy current 가 조금 더 커져서 온도가 점(20, 0)보다 높다.
- ✓ 점 (0,0)과 (0, 46)의 온도는 동일해 보이나 온도 스케일 상 그 차가 작게 보일 뿐이지 경향성은 위의 두 점과 같다.
- ✓ 열원이 일정하게 에너지를 공급하므로 각각의 점은 특정 온도 도달 후 일정하게 온도가 증가한다.

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Case 3 : Magnetic coupled thermal – temperature dependent

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Case 3 : Magnetic coupled thermal – temperature dependent

Description

- Case 2에서는 온도에 따라 재료의 전자계 특성이 변하지 않아 공급되는 열에너지가 일정하였다.

- Case 3에서는 온도에 따라 재료의 전자계 특성이 변하고 이에 따른 온도 분포는 어떻게 될 것인지를 살펴본다.

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Case 3 : Magnetic coupled thermal – temperature dependent

Step 1. Edit the material of the BILLET(STEEL_1)

- B(H)

  Isotropic analytic saturation+knee adjustment *exponential function of T

  Initial relative permeability(ur) : 600

  Saturation magnetization(Js) [T] : 2.0

  Knee adjustment coefficient(α): 0.4

  Temperature constant [℃] : 40

  Curie temperature [℃] : 760

  Default working temperature [℃] : 20

  40 [℃]부터 특성이 변하기 시작하여 760 [℃] 에서 자력 상실

- J(E)

  Isotropic resistivity, linear function of T

  $\rho(T)= \rho_a(1+a(T-T0))$

  - a : 0.004, ρ_a : 2.5e-7
  - Reference temperature (T0) : 0, CELSIUS_DEGREE
  - Default working temperature : 20, CELSIUS_DEGREE

  1 [℃] 상승하는데 비저항이 0.4 % 씩 증가

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Case 3 : Magnetic coupled thermal – temperature dependent

Step 1. Edit the material of the BILLET(STEEL_1)

- k(T)
  Isotropic linear function of T
  $k=k_a(1+a(T-T0))$
  a : -2.5e-4
  k_a : 47 [W/m/℃]
  Reference temperature T0 : 0, CELSIUS

온도가 증가할수록 열전달률이 감소한다.
500[℃] 증가 시, 열전달율이 12.5% 감소한다.

- RCP(T)
  Gaussian function of T + exponential
  Energy of phase transition [J/m3] : 1.2e-11
  $\rho Cp(T)=\rho Cp_i+(\rho Cp_0-\rho Cp_i)*\exp(-T/T_{au})+\rho Cp_{gauss}(T)$
  - Specific heat capacity ρCρ0 [J/m3/℃] : 3.9e+6
  - Specific heat capacity ρCρi [J/m3/℃] : 4.68e+6
  - Gaussian standard deviation σ [℃] : 30
  - Temperature constant T_{au} [℃] : 500
  - Temperature of phase transition Tc [℃] : 760

온도가 증가할수록 열용량이 증가하나 무한히 증가하지는 않는다.

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Case 3 : Magnetic coupled thermal – temperature dependent

Step 2. Solving(Scenario)

Name	Parameter control							
	Controlled Parameter	Interval						
		Lower limit (s)	Higher limit (s)	Variation Method	Initial step value (s)	Min step value (s)	Max step value (s)
SCENARIO_1	TIME	0.0	4	Adaptative step	0.005	5.0e-6	0.05
		4	6	Adaptative step	0.05	5.0e6	0.2

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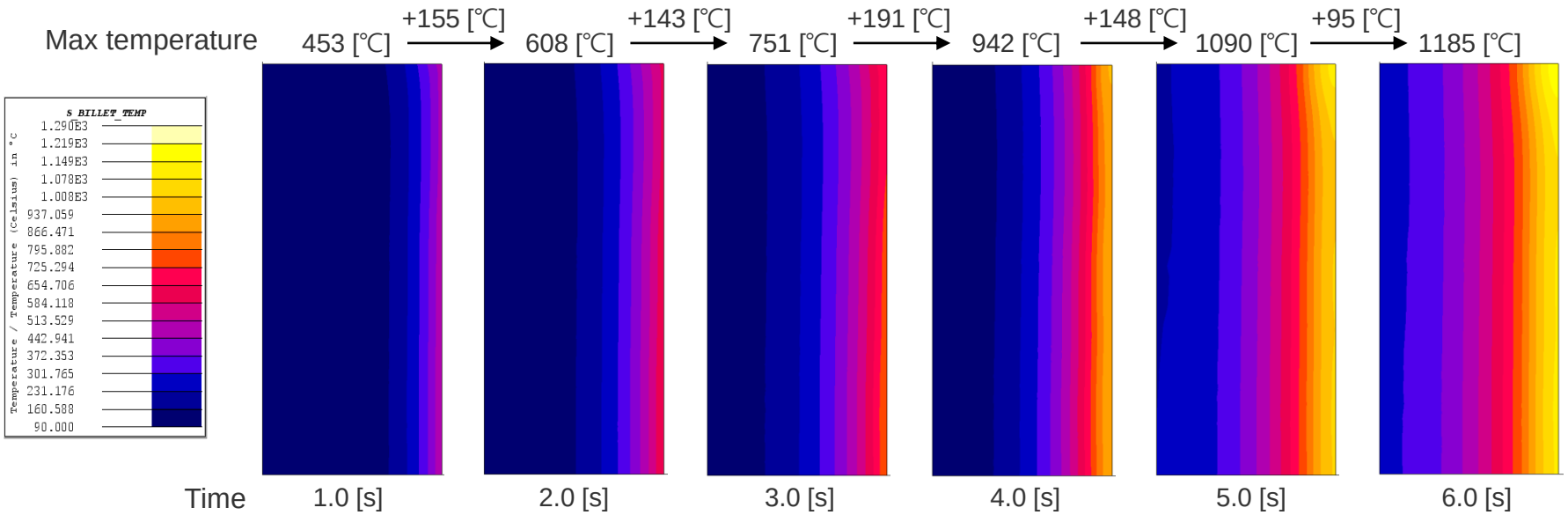
Case 3 : Magnetic coupled thermal – temperature dependent

Step 3. Post process

- Temperature distribution



✓ 3초 때 급증가 하고, 5초 때 증가율이 떨어졌다.
✓ 온도에 따라 전자계 및 열 특성이 바뀌어 열원이 일정하게 에너지를 공급하지 않기 때문이다.

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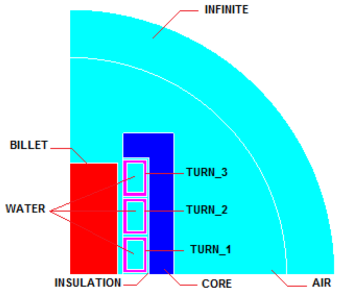
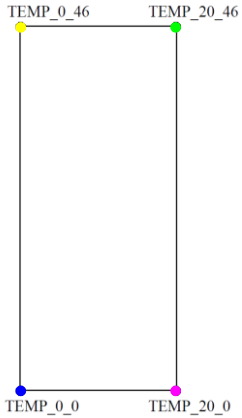
Case 3 : Magnetic coupled thermal – temperature dependent

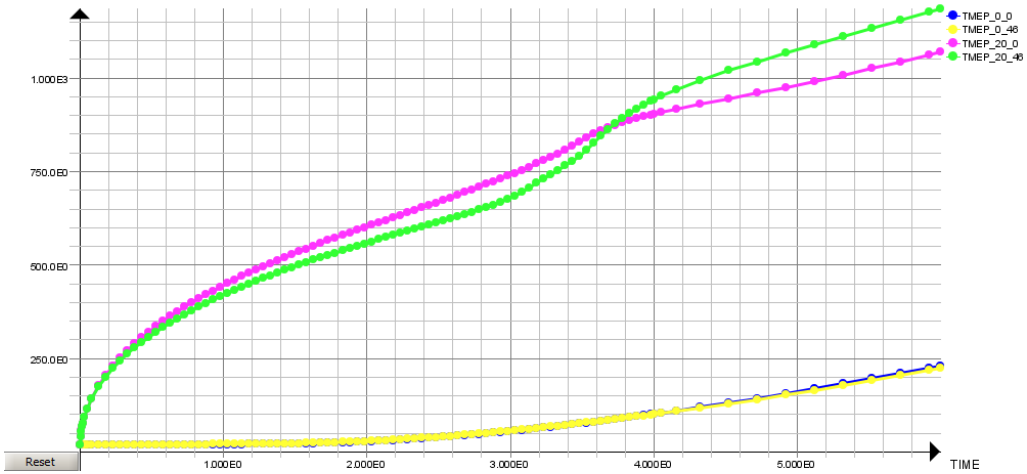
Step 3. Post process

- Temperature at the points





<BILLET>



✓ BILLET 부분별로 온도 증가가 다르고 온도에 따른 저항도 다르기 때문에 그래프가 평행하지 않는다.
✓ 점(20, 46)은 3~4초 사이에서 온도가 급증하고 이 구간에서 760[℃]를 넘어 자기특성이 없어지는 부분이 생기는데 이것에 의하여 eddy current 패턴이 바뀌기 때문이다.

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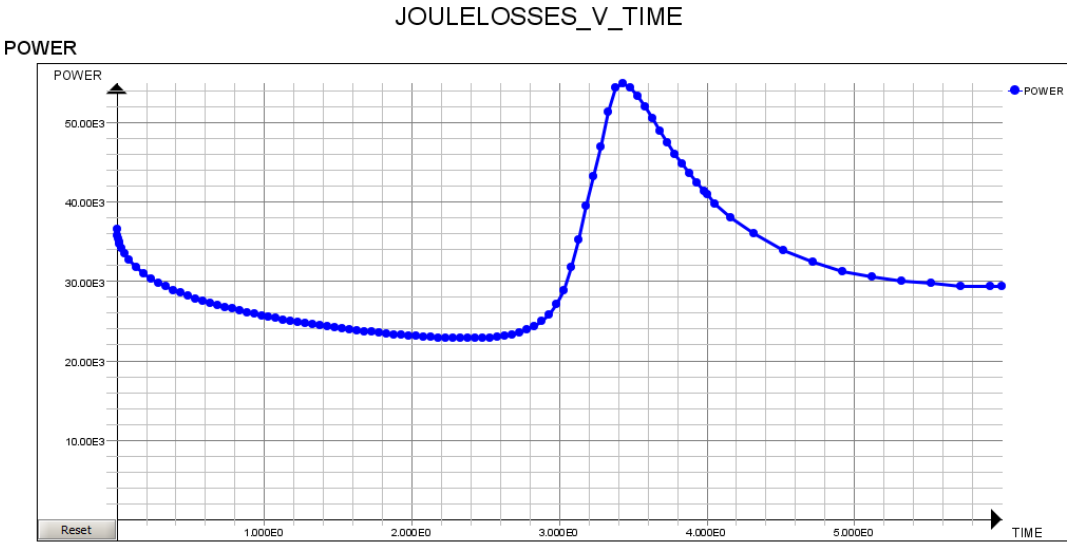
Case 3 : Magnetic coupled thermal – temperature dependent

Step 3. Post process

- Comparison of temperature at the points



- ✓ 3~4초사이에 eddy current 갑자기 증가하기 때문에 온도가 증가한 것이다.
- ✓ TURN 의 전원 전류의 자계는 BILLET 에 eddy current 를 생성시키는데 반대로 BILLET 의 eddy current 의 자계 또한 TURN 코일에 eddy current 를 발생시킨다.
- ✓ TURN에 생기는 eddy current 는 전원전류를 감소시킨다.
- ✓ 3~4초 사이 BILLET 의 자기특성이 없어지면서 TURN에 생기는 eddy current 도 작아져 전원전류가 급증하였고, 이에 따라 BILLET의 eddy current 도 급증한 것이다.
- ✓ BILLET 의 eddy current 가 TURN 코일에 영향을 크게 미치므로 BILLET 과 TURN 코일 사이 거리가 너무 가깝게 설정되었다.

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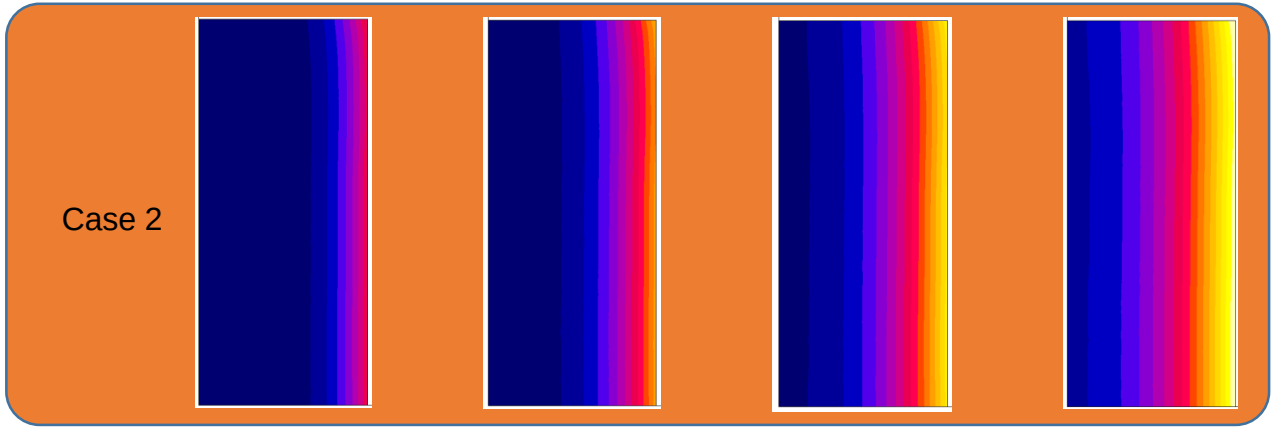
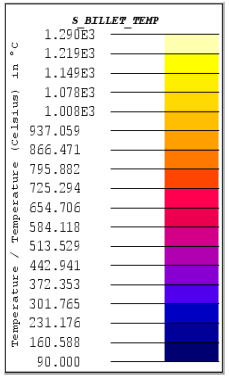
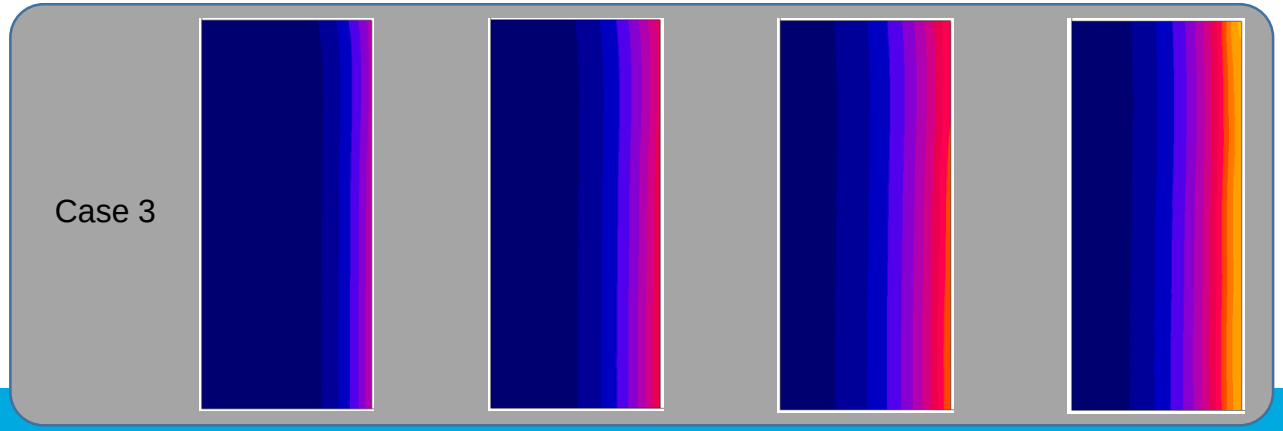
- Temperature comparison between Case 2 and Case 3





1.0 [s] 2.0 [s] 3.0 [s] 4.0 [s]



✓ 온도 변화에 따른 전자계 및 열특성이 반영 되어 실제로는 온도가 덜 올라 가는 것을 알 수 있다.

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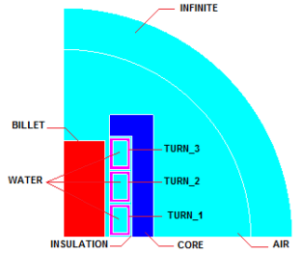
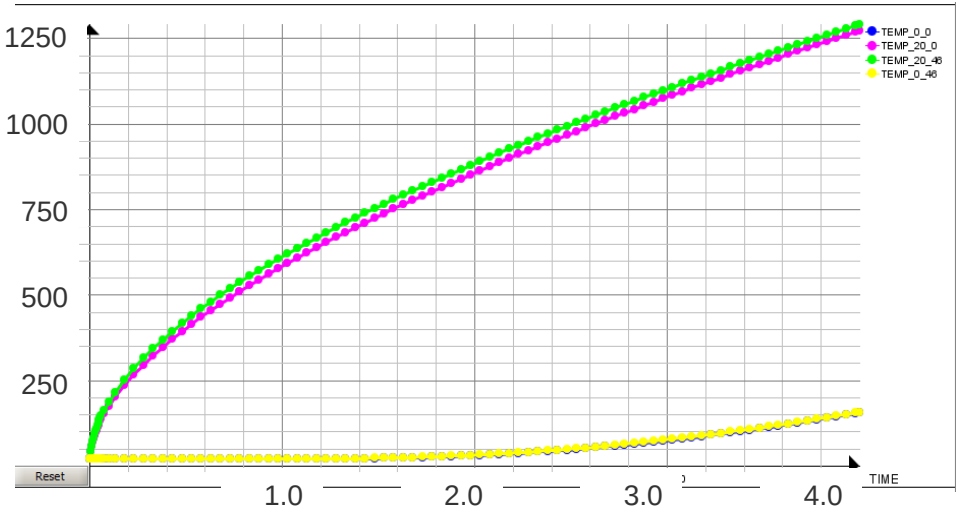
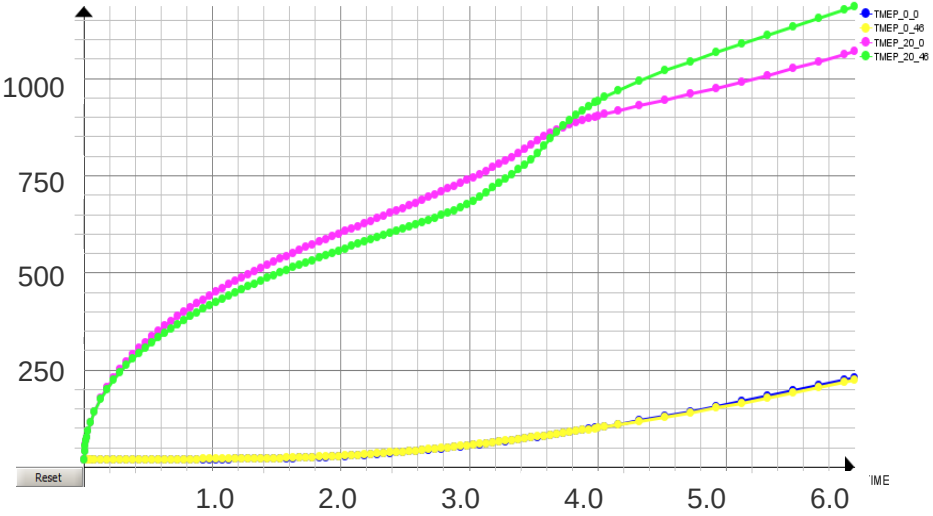
Case 3 : Magnetic coupled thermal – temperature dependent



Step 3. Post process

- Comparison of temperature at the points





✓ Case 3은 BILLET 의 온도에 따라 저항이 증가하기 때문에 eddy current 가 Case 2보다 작아 온도 증가율이 낮다.

✓ Case 3에서 점(20, 46)은 Case 2와 달리 점(20, 0)보다 온도가 낮은데 점(20, 46) 부분이 공기와 접촉하기 때문에 쿨링 효과가 작용하기 때문이다.

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Summary & Conclusion

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Summary & Conclusion

- Case 2와 Case 3의 비교를 통해 온도에 따른 특성변화가 결과에 영향을 미치므로 온도와 중요한 변수일 때는 열해석을 동반하여야 한다.

- 기존의 전자계 해석 세팅에서 문제정의 및 물성 설정 수정만으로 쉽게 열해석을 할 수 있다.

- Induction heating에 대해 알 수 있었고, Case 3의 결과로 BILLET 과 TURN 코일의 적정거리를 찾는다면 좀 더 열효율을 더 높일 수 있는 가능성을 보았다.

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