핫!-브레이크

권태욱, 정진하, 함제현

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정진하

- Simulink 해석
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- MATLAB verification code 작성

함제현

- Comsol 해석

2. 프로젝트 구상 배경 및 목표

ABS 시스템의 유무에 따른
차량의 제동 특성과 브레이크 온도 해석

2. 프로젝트 구상 배경 및 목표

브레이크 패드

동역학 시간

3. Simulink 해석

차량의 parameter 정보를 활용하여

브레이크 상태를 관찰하기 위한 종방향 차량동역학 모델 제작

```
%% Parameters
clear, clc, close all

% Vehicle Parameters
m=380;
%m = 716.92; % Vehicle weight, including air drag [kg]
lf = 0.9661; % Length of front wheel center to CG [m]
l = 1.58; % Wheelbase [m]
lr = l-lf; % Length of Rear wheel center to CG [m]
h = 0.3247; % CG Height [m]

% Wheel-tire Parameters
I_wheel =0.835; % wheel inertia 0.784+0.051 [kg*m^2]
r_load = 0.2; % loaded radius [m]
rw = 0.254; % Unloaded radius [m]
phi = acos(r_load/rw);
r_eff = rw * sin(phi)/phi; % Effective radius [m]

% Aero Resistance
Af = 1.134; % Frontal Area [m^2]
Cd = 1.79; % Drag coefficient
Cl = 3.76;

% Rolling Resistance
R_roll = 0.015; % Rolling resistance coefficient

% Initial value
x_0 = 0; % Initial position [m]
vel_I=130/3.6; % Initial velocity [m/s]

% Environment Parameters
g = 9.81; % gravitational acceleration [m/s^2]
rho = 1.225; % air density [kg/m^3]

% Tire coefficient, Dry asphalt
B=10;
C=1.9;
D=1;
E=0.97;
```

3. Simulink 해석

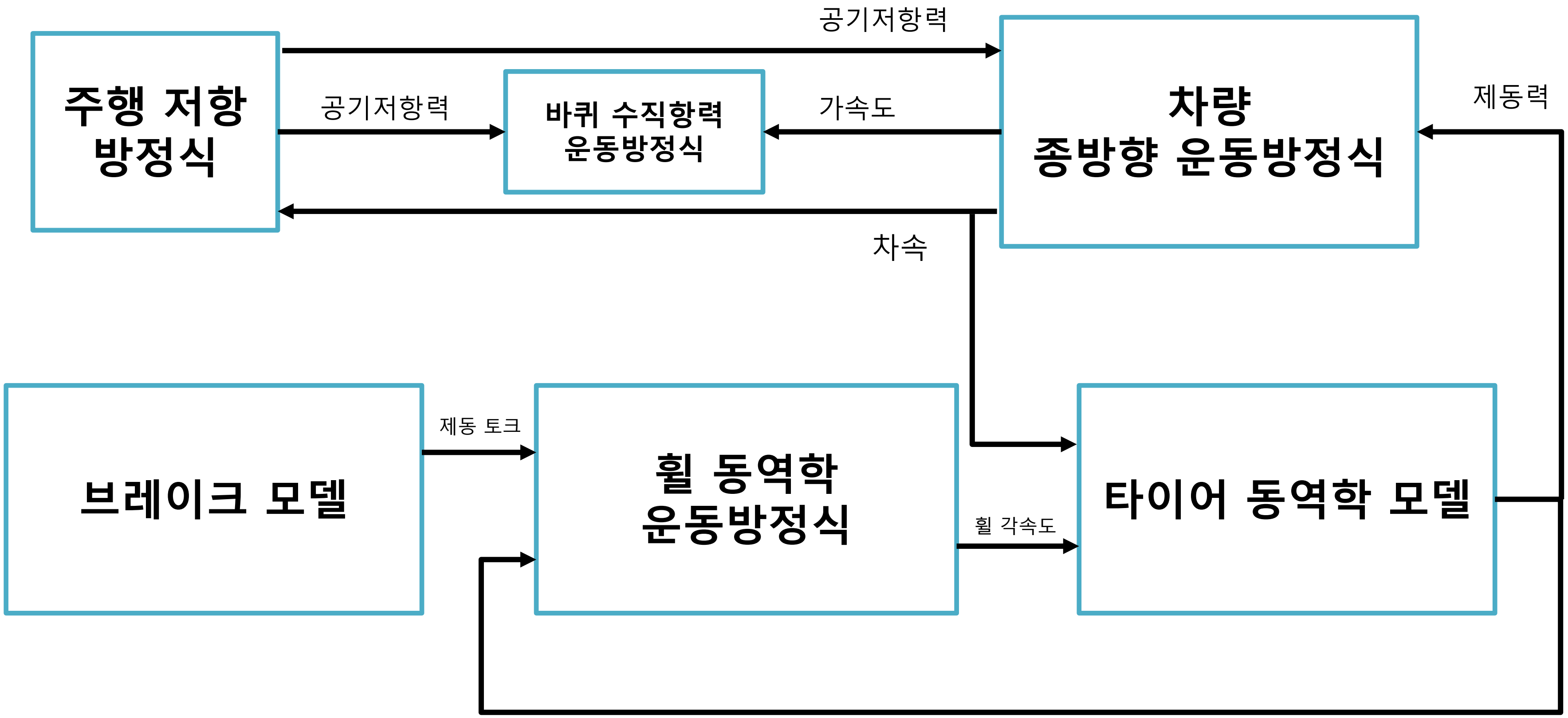
<가정>

1. 기울기, 뱅크각이 없는 평탄한 마른 노면

-> 조향, 서스펜션, 노면 기울기에 의한 힘을 고려하지 않는 1 DOF Model

2. 일반적인 성능의 타이어 사용 (Pacejka Magic Formula)
3. 130km/h의 초기 속도에서, 최대 제동력을 사용하여 급제동

3. Simulink 해석



3. Simulink 해석

브레이크 모델

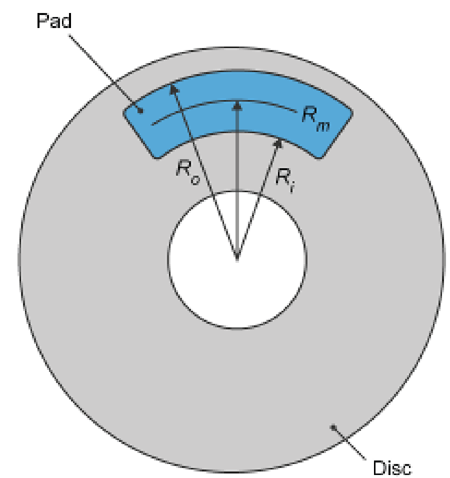
전륜의 Pad에서 발생하는 최대 압력

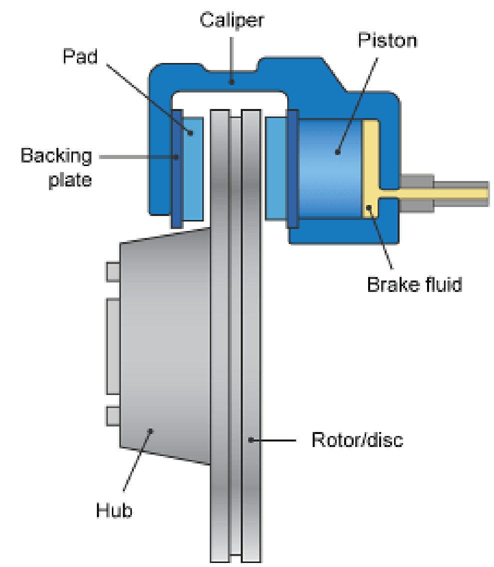
$$F_{caliper} = P_{master} \times A_{caliper}$$

$$T_{brake} = F_{caliper} \times \mu_{pad} \times R_{eff}$$

$$R_{eff} = \frac{{r_{out}}^3 - {r_{in}}^3}{{r_{out}}^2 - {r_{in}}^2}$$

T_{brake}=1138.99 Nm



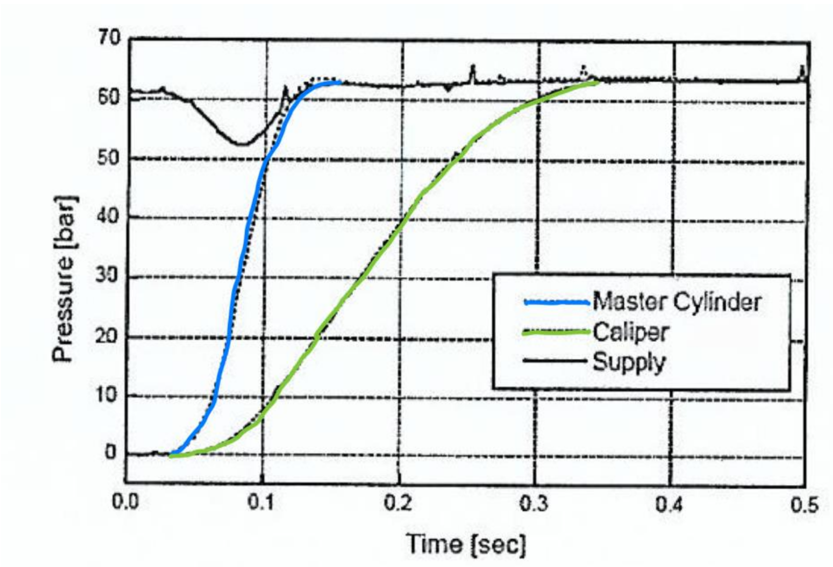



```
% Brake parameters
P=88.70169877*10^5; % [N/m^2]
P0=7*10^4; % [N/m^2]
Area_C=490.87e-6;
BF=0.7*4; % Pad coefficient*4
r_bout=0.1085;r_bin=0.0825;
r_Beff=2/3*(r_bout^3-r_bin^3)/(r_bout^2-r_bin^2);
T_b=(P-P0)*Area_C*0.98*BF*r_Beff;
```

3. Simulink 해석

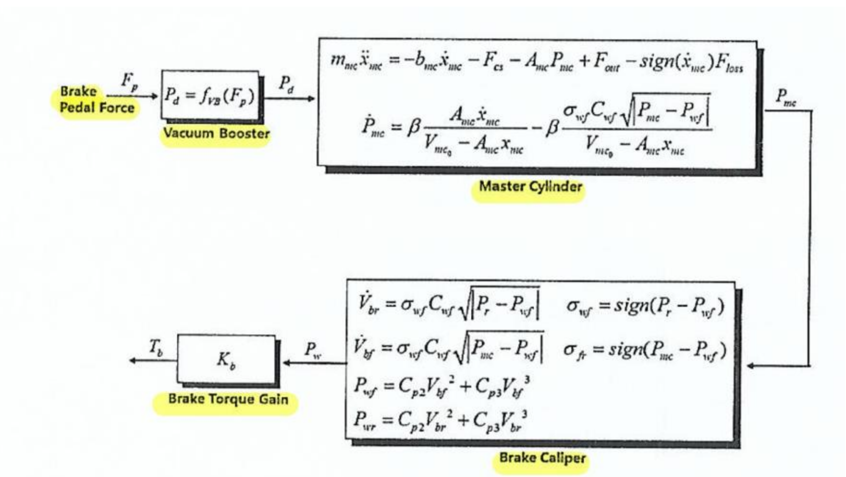
브레이크 모델

Brake test Results



0.3s 의 lag time

Nonlinear brake models

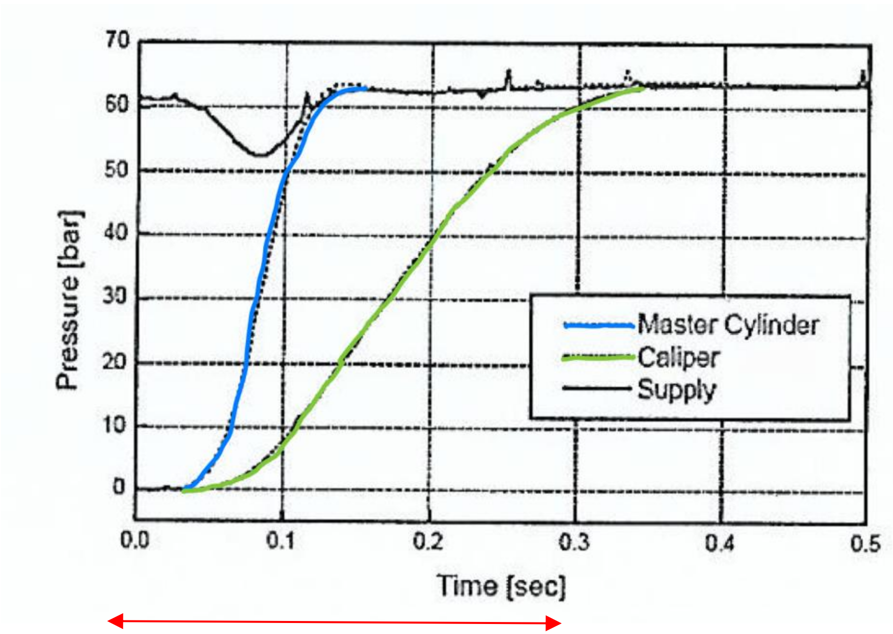


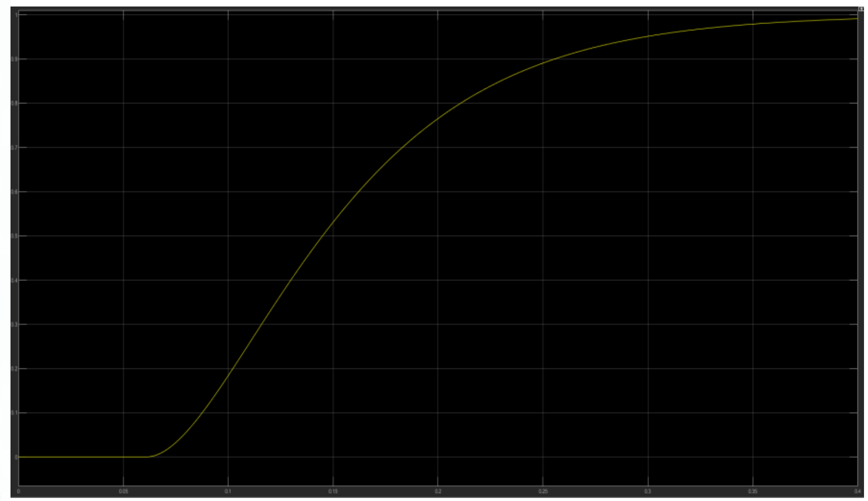
Brake model을 2차 시스템으로 근사 가능

3. Simulink 해석

브레이크 모델

Brake test Results





Brake model을 2차 시스템으로 근사 가능

0.3s 의 lag time

3. Simulink 해석

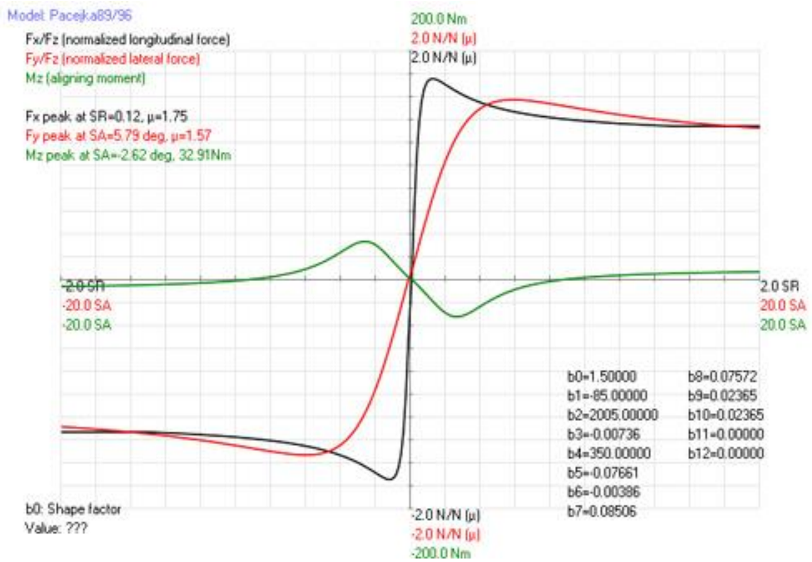
타이어 동역학 모델

Pacejka Magic Formula

타이어에서 슬립율에 따른 제동력을 나타내는 경험식

$$F_x = F_z \cdot D \cdot \sin(C \cdot \arctan\{B\sigma - E \cdot (B\sigma - \arctan(B\sigma))\})$$

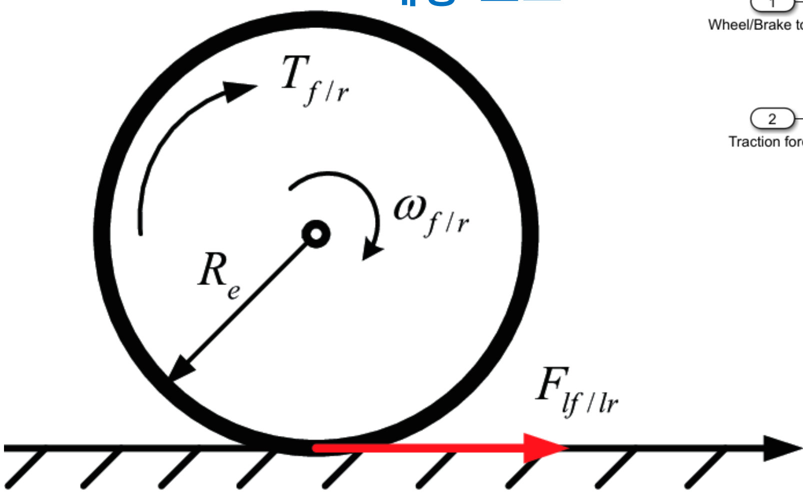
감속 시, 슬립율 $\boldsymbol{\sigma_x = \frac{r_{eff}\omega - V_x}{r_{eff}\omega}}$



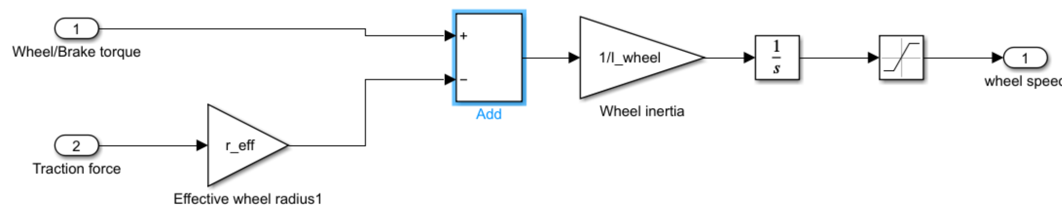
3. Simulink 해석

휠 동역학 운동방정식

제동 토크



제동력(Traction Force)

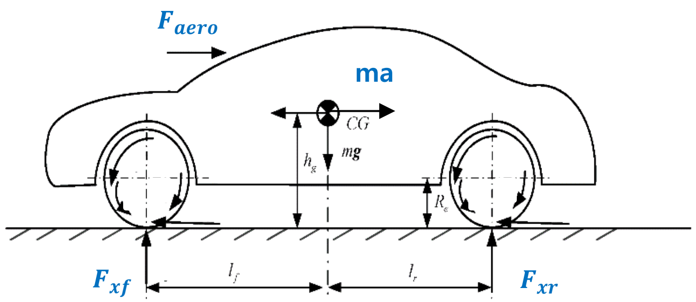


$$I_w \dot{\omega} = T_f - R_e F_{lf}$$

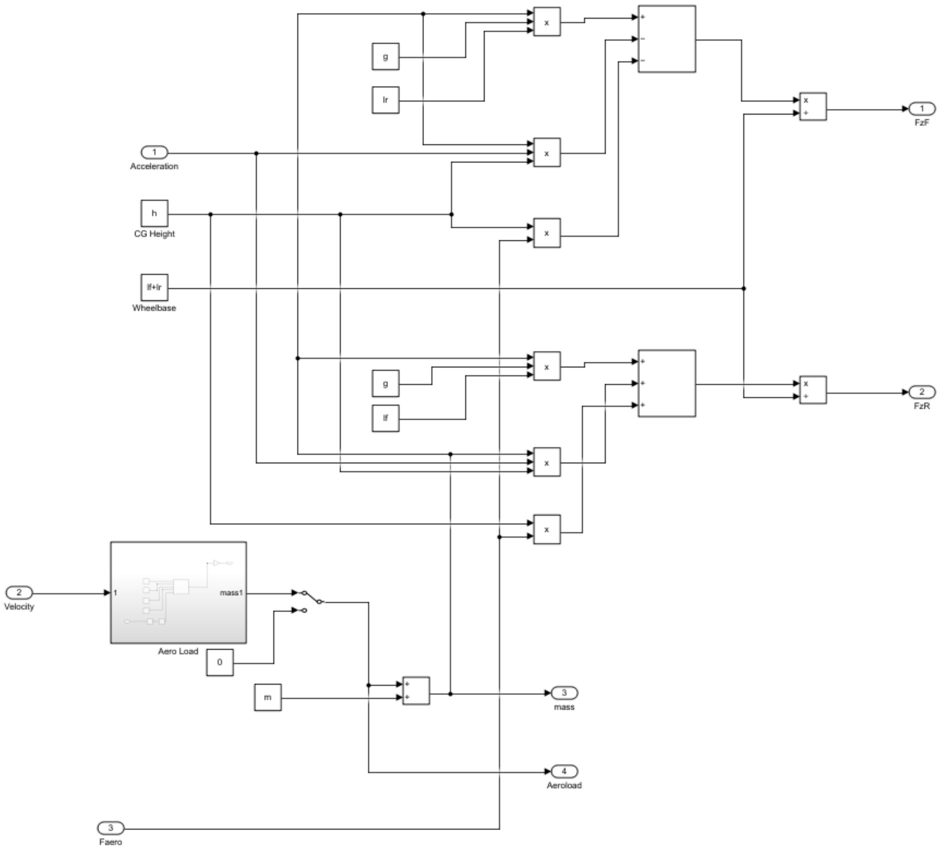
식을 통해 각속도를 도출

3. Simulink 해석

차량 종방향 운동방정식



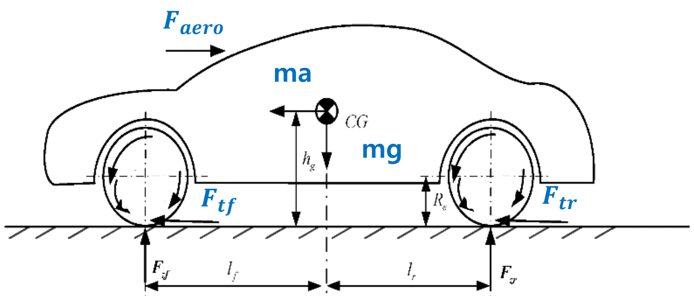
$$(l_f + l_r)F_{zf} + mah - mgl_r + F_{aero}h = 0$$
$$(l_f + l_r)F_{zr} - mah - mgl_f - F_{aero}h = 0$$

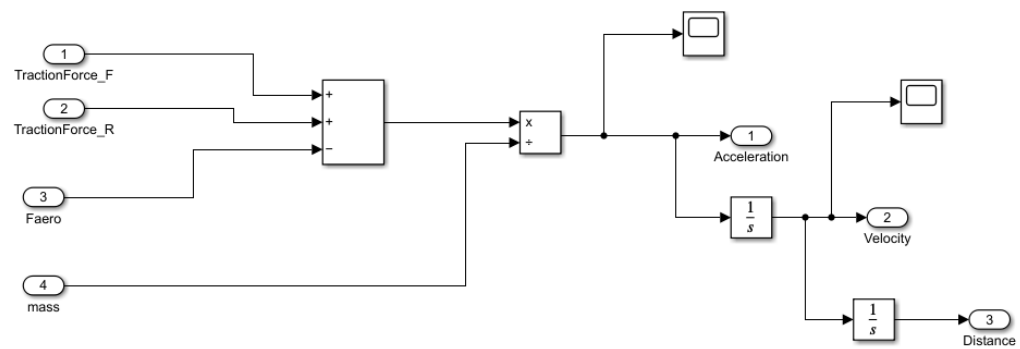


제동 시의 동적 하중 분배를 계산

3. Simulink 해석

차량 종방향 운동방정식



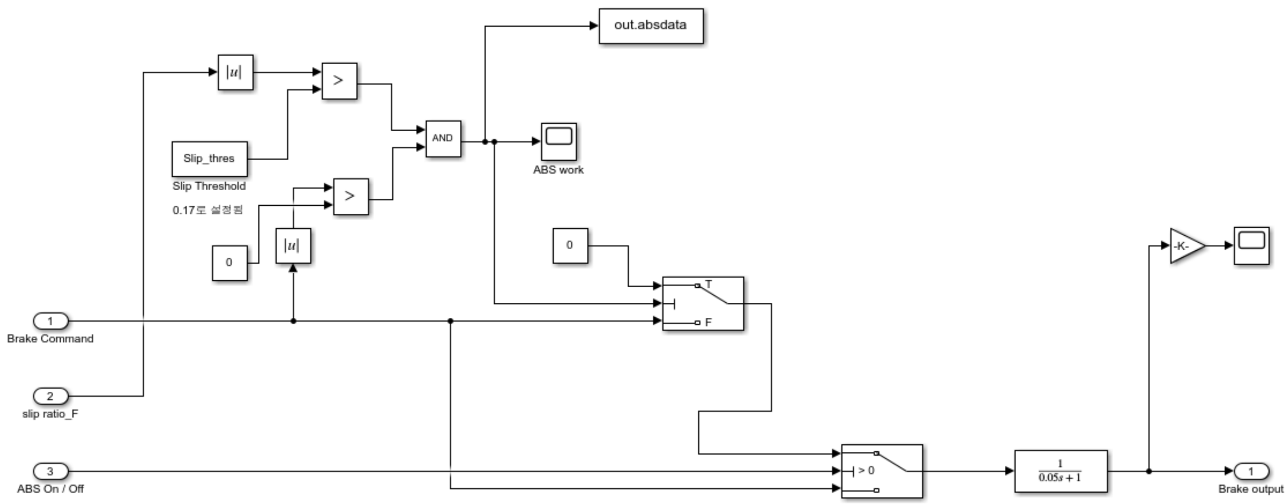


$$ma = F_{xf} + F_{xr} - F_{aero}$$

제동 시의 가속도, 속도(차속), 이동거리 계산
mass는 down force를 고려한 Aero load를 포함

3. Simulink 해석

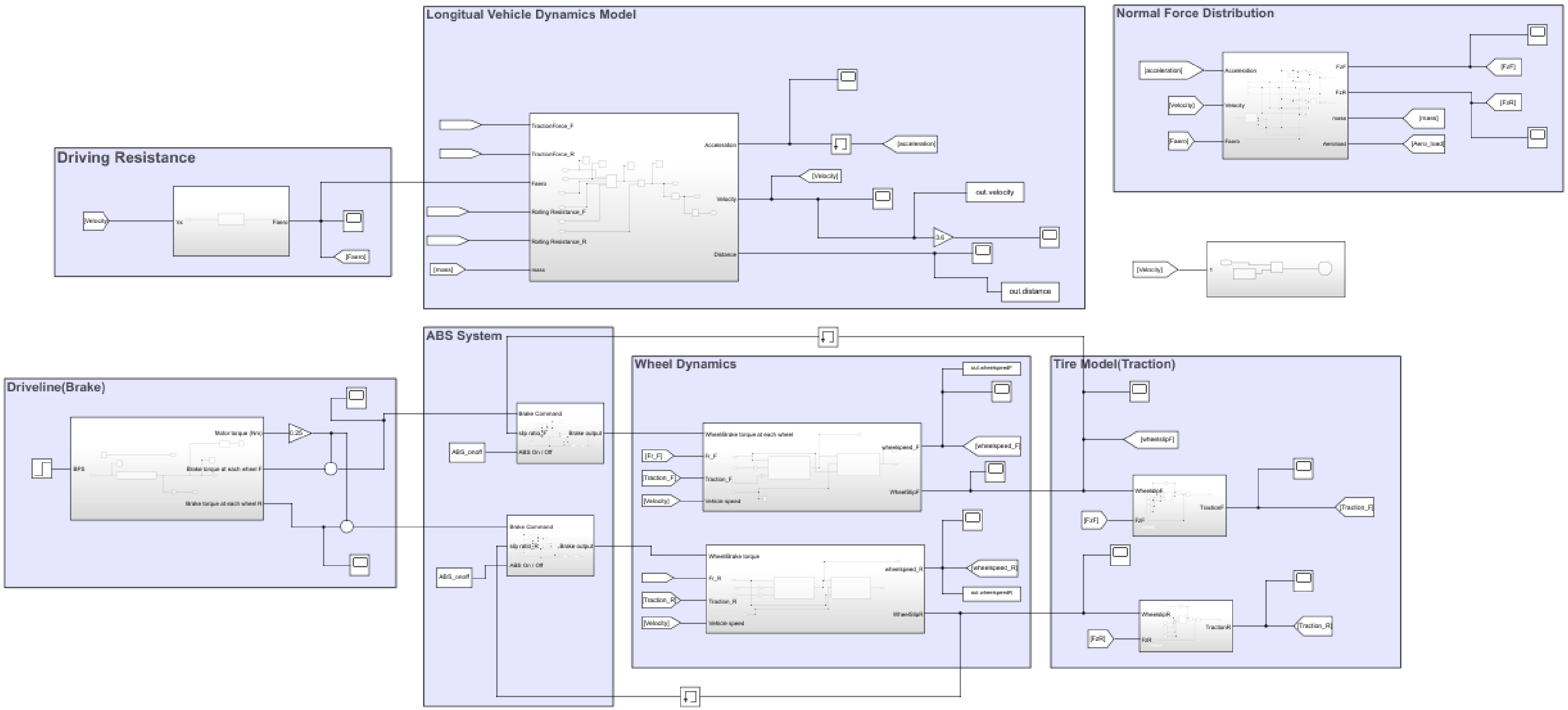
ABS (Anti Lock Braking System)



Traction Force가 최대가 되는 목표 슬립율 0.17에 따라
브레이크 입력을 on/off하여 Traction Force를 극대화

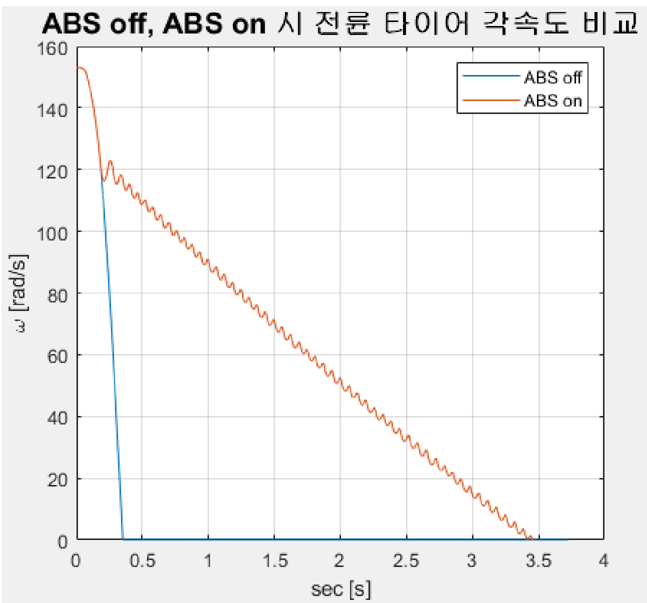
3. Simulink 해석

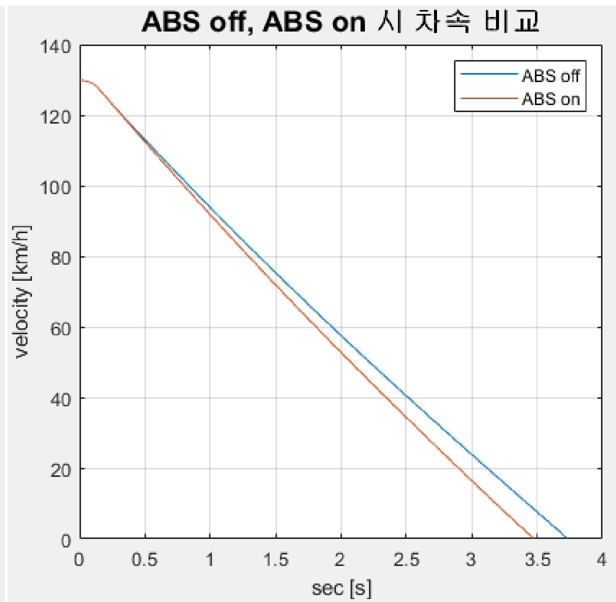
완성된 Simulink 모델

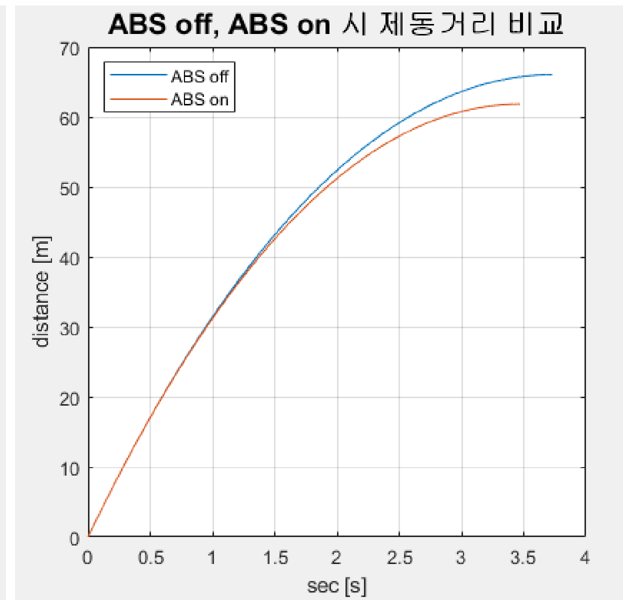


3. Simulink 해석

시뮬레이션 결과(ABS, Non ABS 비교)







ABS off의 경우

제동 시간: 3.72s

제동 거리: 66.03m

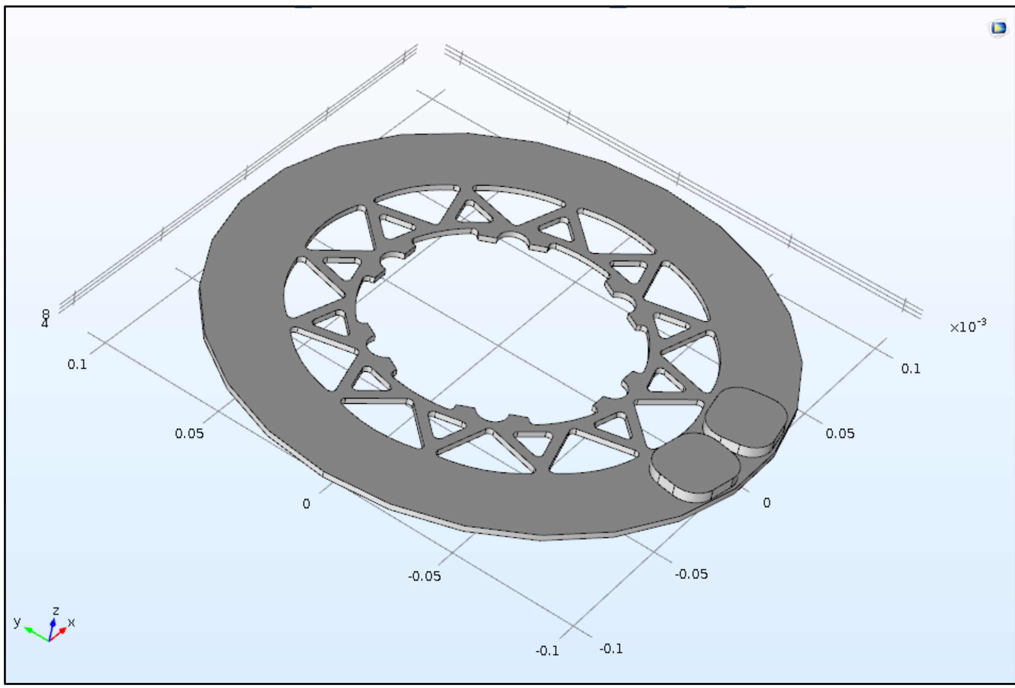
Wheel Lock-up이 걸리는 시간: 0.35s

ABS on의 경우

제동 시간: 3.47s (0.25s 단축)

제동 거리: 61.8m (4.28m 단축)

4. COMSOL 해석



<Brake Disc & Pad>

Panic Brake

Panic Brake with ABS

4. COMSOL 해석

The Heat Transfer in Solids Interface solves for the following equation derived from Equation 4-13:

$$\rho C_p\left(\frac{\partial T}{\partial t} + \mathbf{u}_{\mathrm{trans}} \cdot \nabla T\right) + \nabla \cdot (\mathbf{q} + \mathbf{q}_{\mathrm{r}}) = -\alpha T : \frac{dS}{dt} + Q \qquad (4\text{-}14)$$

<COMSOL 에서 풀어내는 식>

4. COMSOL 해석

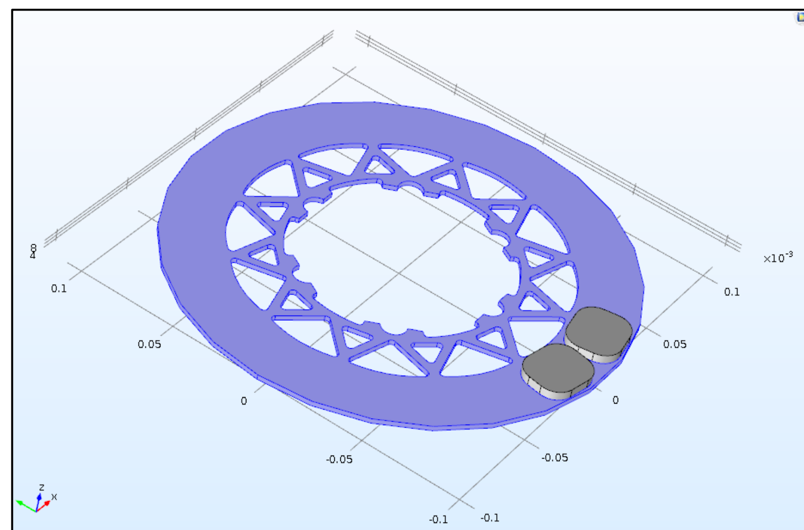
The Heat Transfer in Solids Interface solves for the following equation derived from Equation 4-13:

$$\rho C_p\left(\frac{\partial T}{\partial t} + \boxed{\mathbf{u}_{\mathrm{trans}} \cdot} \nabla T\right) + \nabla \cdot (\mathbf{q} + \mathbf{q}_{\mathrm{r}}) = -\alpha T : \frac{dS}{dt} + Q \qquad (4\text{-}14)$$

<COMSOL 에서 풀어내는 식>

Velocity field:

$\mathbf{u}_{\mathrm{trans}}$	-y*omega(t)	x	m/s
	x*omega(t)	y	
	0	z	



4. COMSOL 해석
– Boundary Condition

Heat Source

Thermal Symmetry

Diffusion

Convection

4. COMSOL 해석
– Boundary Condition

Heat Source

$$\dot{q} = -k\frac{\partial T}{\partial x} = \left(\begin{array}{c}\text{Heat flux in the} \\ \text{positive } x - \text{direction}\end{array}\right) \qquad (\mathrm{W/m^2})$$

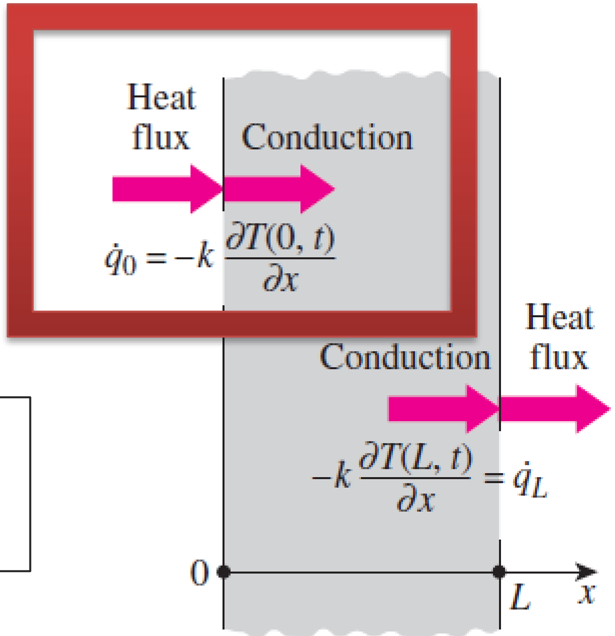


FIGURE 2–28

Specified heat flux boundary conditions on both surfaces of a plane wall.

4. COMSOL 해석
– Boundary Condition

Heat Source

$$E_b = mV_1^2 / 2 + I\omega_1^2 / 2$$

<Braking Energy>

4. COMSOL 해석
– Boundary Condition

Heat Source

$$E_b = mV_1^2 / 2 + I\omega_1^2 / 2$$

<Braking Energy>

$$P_b = -\frac{d}{dt}(E_b)$$

<Braking Power>

4. COMSOL 해석
– Boundary Condition

Heat Source

$$P_b = -\frac{d}{dt}(E_b)$$

<Braking Power>

$$P_b = -\frac{d}{dt}\frac{E_b}{8}$$

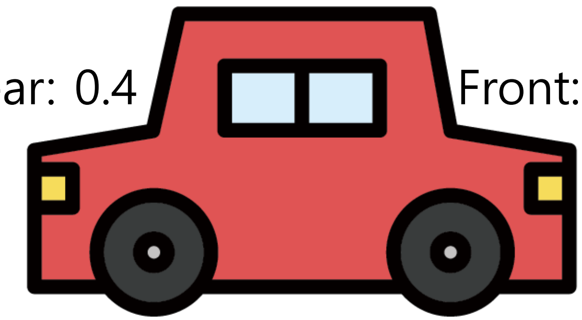
<Braking Power for One-Half Disc>

4. COMSOL 해석
– Boundary Condition

Heat Source

<Braking Force Dissipation>

Rear: 0.4



Front: 0.6

$$P_b = -\frac{d}{dt}\frac{E_b}{8}$$

<Braking Power for **One-Half Disc**>

$$P = -\frac{E_b * \boxed{0.6}}{4}$$

<Modified Braking Power>

○ General source

◉ Overall heat transfer rate

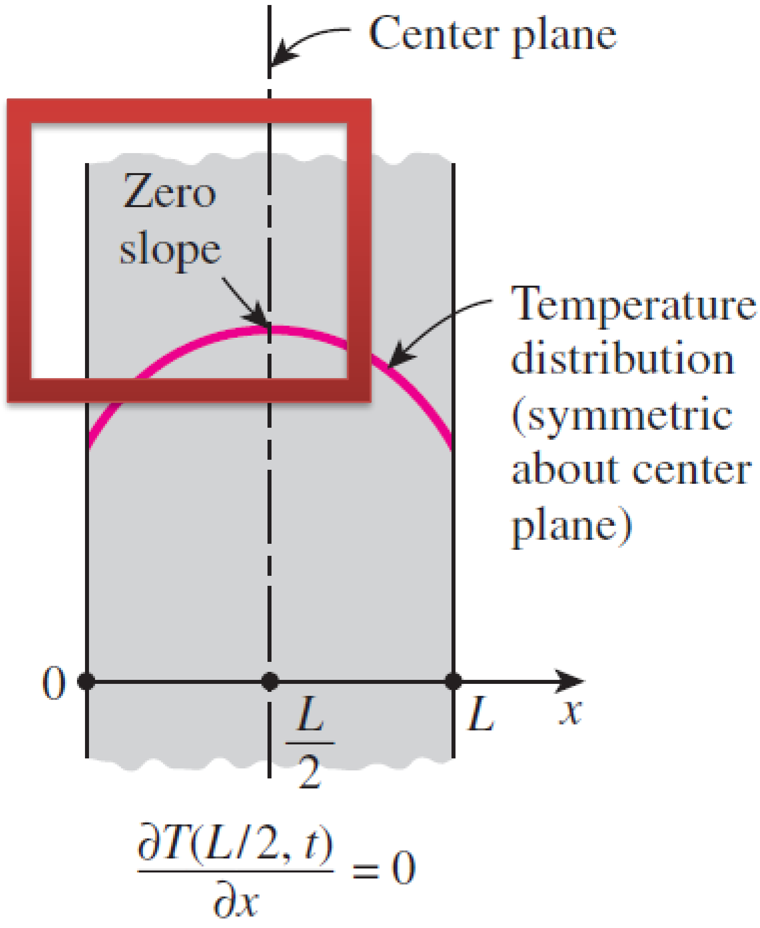
$Q_b = \frac{P_b}{A}$

P_b -I_tire*omega(t)*alpha(t)+(-m_car*v(t)*a(t)*1/2*0.6*1/2)*step_b(t) W

4. COMSOL 해석
– Boundary Condition

Thermal Symmetry

$$\frac{\partial T(L/2, t)}{\partial x} = 0$$



4. COMSOL 해석
– Boundary Condition

Convection

$$-k\frac{\partial T(L,t)}{\partial x} = h_2[T(L,t) - T_{\infty 2}]$$

-> COMSOL에서 Translation 설정 시 자동 반영

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{u}_{(x,y,z)} \cdot \nabla_{(x,y,z)}$$

The right-hand side of this relation shows a new term $\mathbf{u} \cdot \nabla$ corresponding to convection in the case of fluids, or convected quantity by translational motion of a solid.

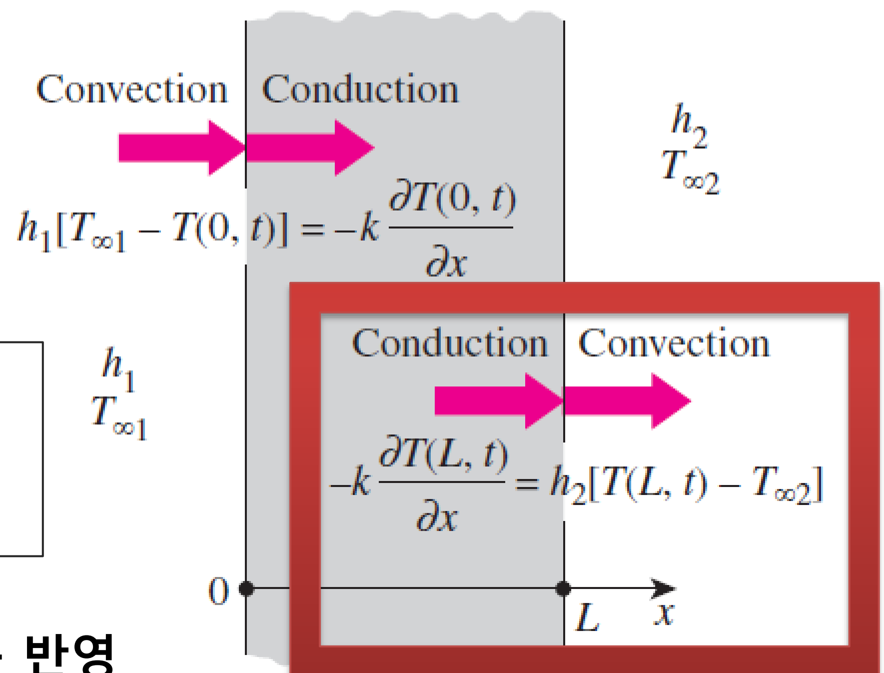


FIGURE 2–32

Convection boundary conditions on the two surfaces of a plane wall.

4. COMSOL 해석
– Boundary Condition

Diffusion

$$-k\frac{\partial T(L,t)}{\partial x} = \varepsilon_2\sigma[T(L,t)^4 - T_{\text{surr},2}^4]$$

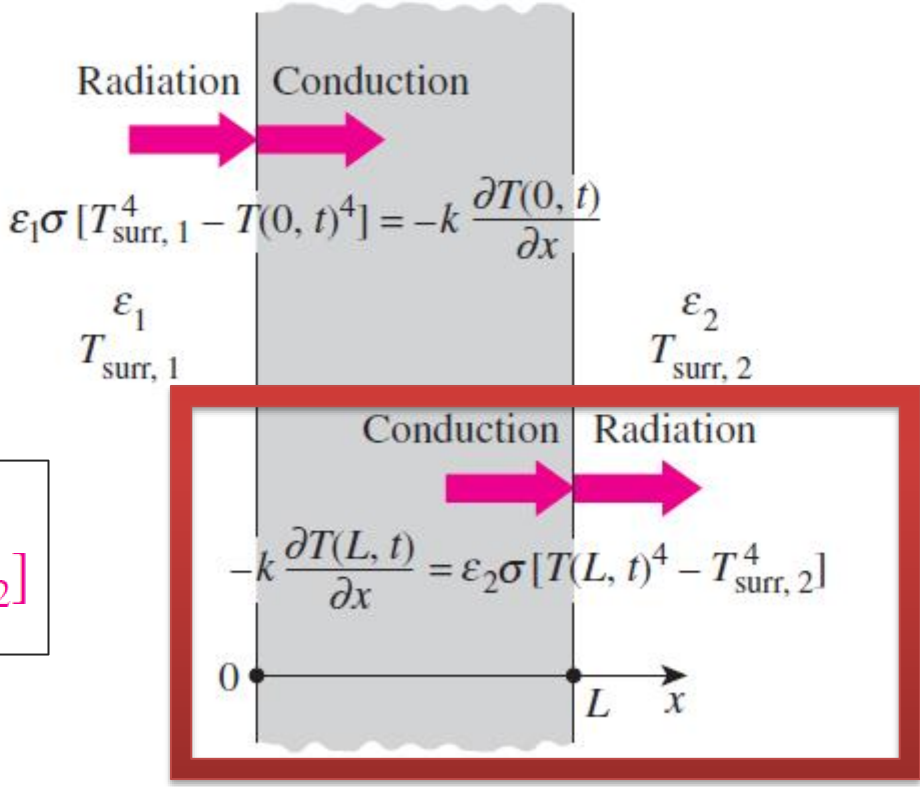
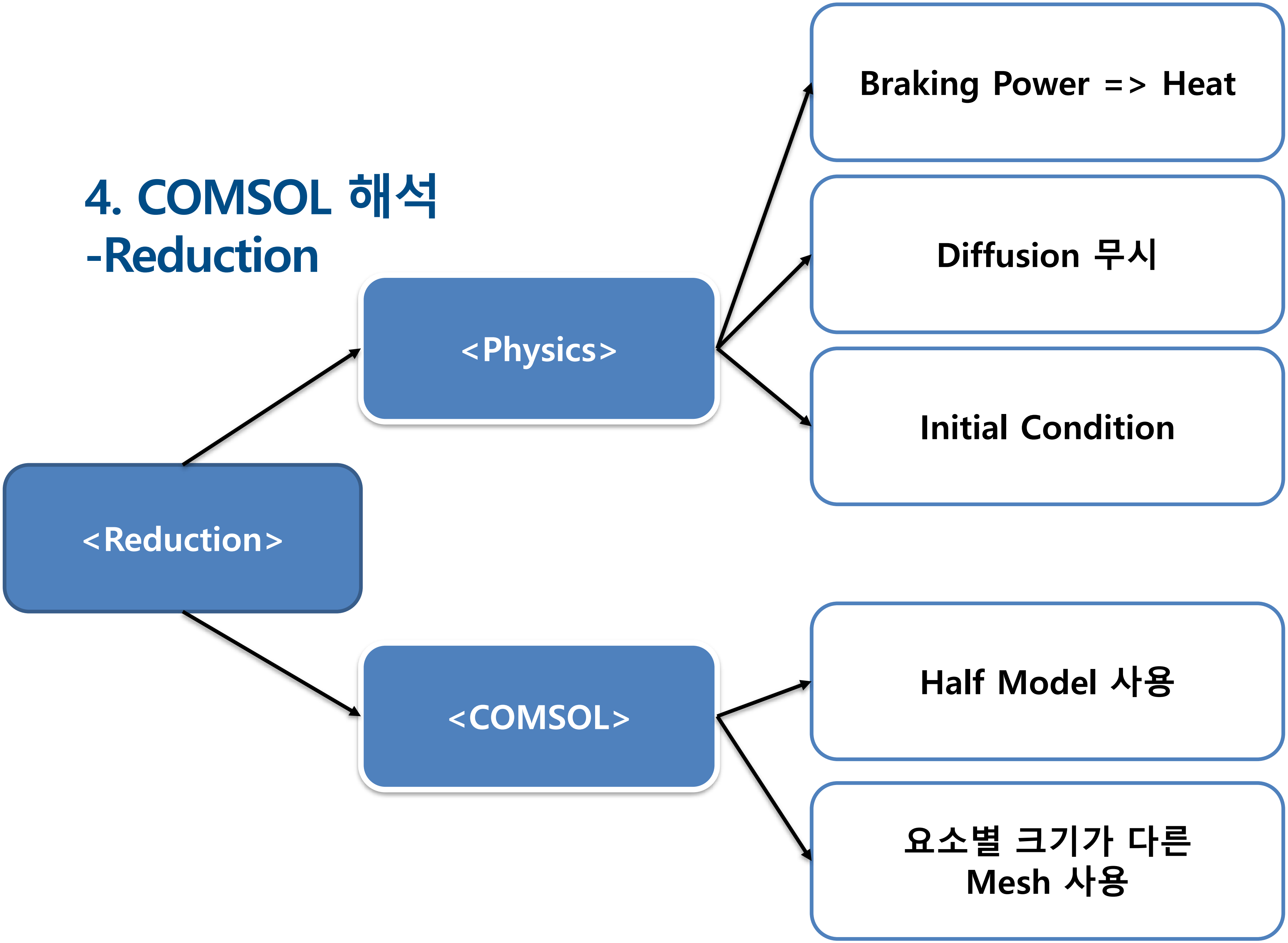


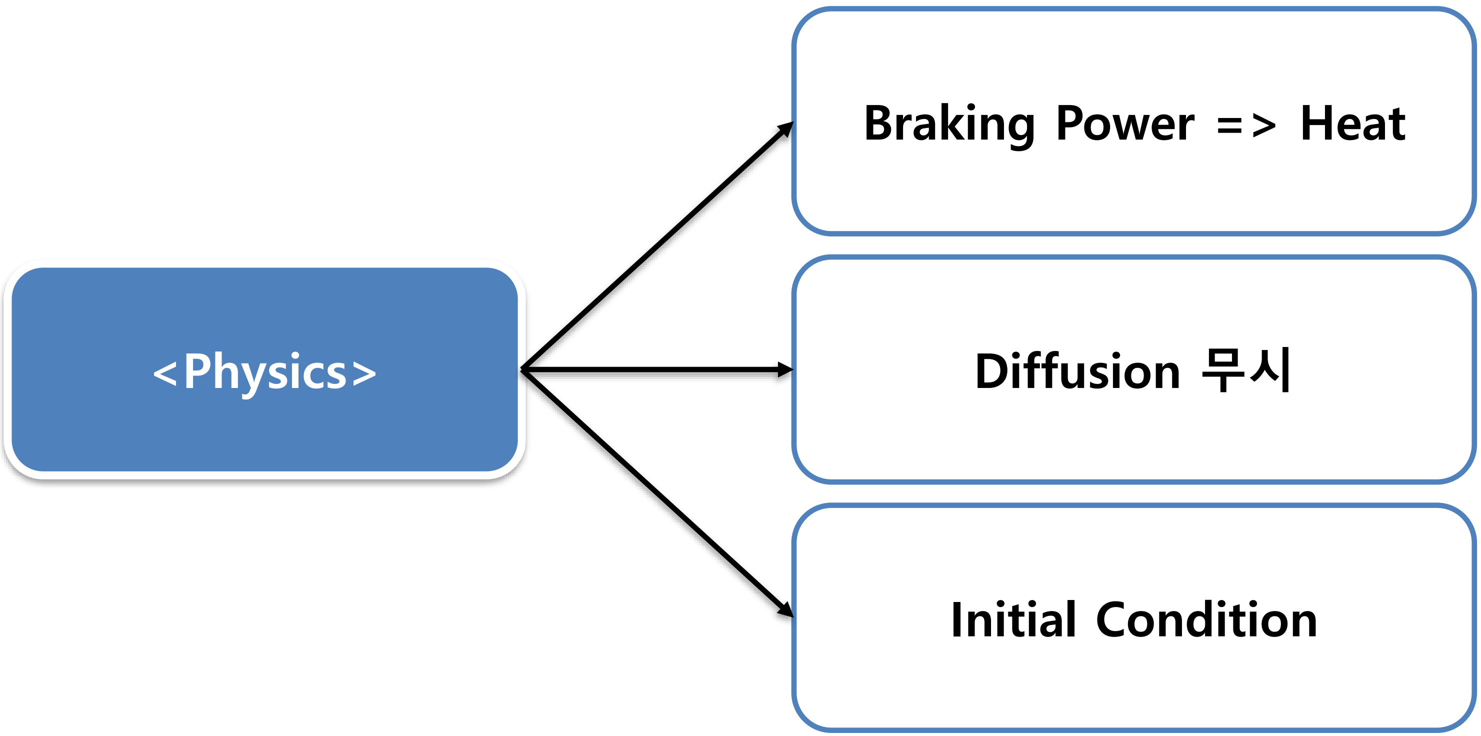
FIGURE 2–35

Radiation boundary conditions on both surfaces of a plane wall.

4. COMSOL 해석
-Reduction



4. COMSOL 해석
-Reduction



4. COMSOL 해석
-Reduction

<Physics>

Braking Power => Heat

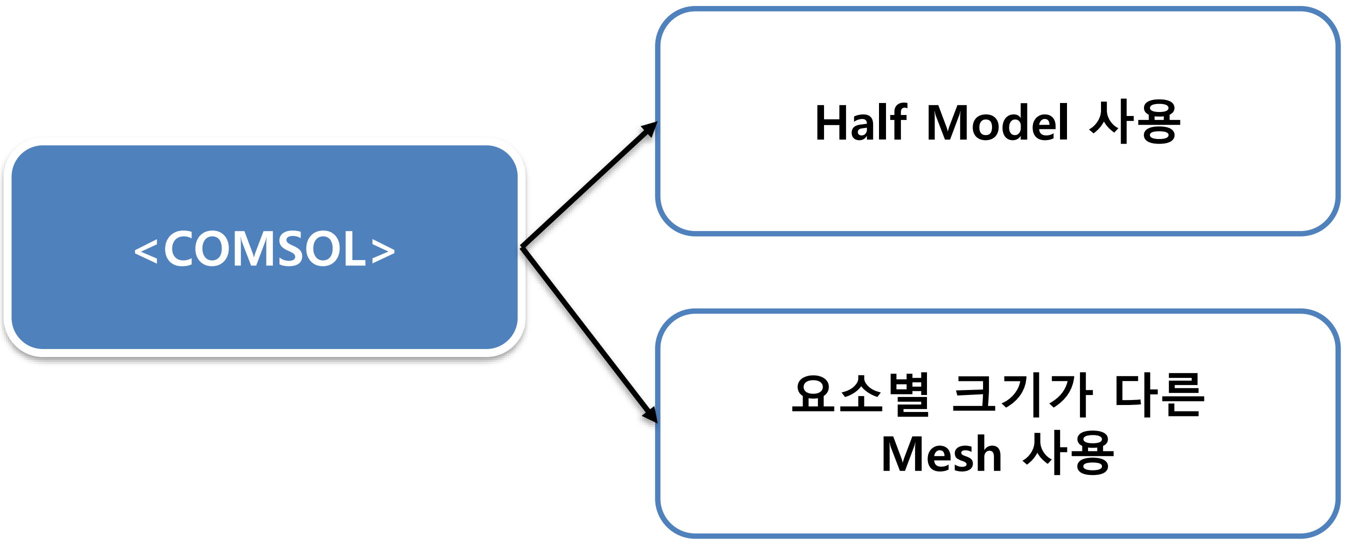
<u>*모든 Braking Power는 Heat Flux로 반영됨</u>

4. COMSOL 해석
-Reduction

<Physics>

Diffusion 무시	→	효과 미미함
Initial Condition	→	디스크와 대기 온도가 같음

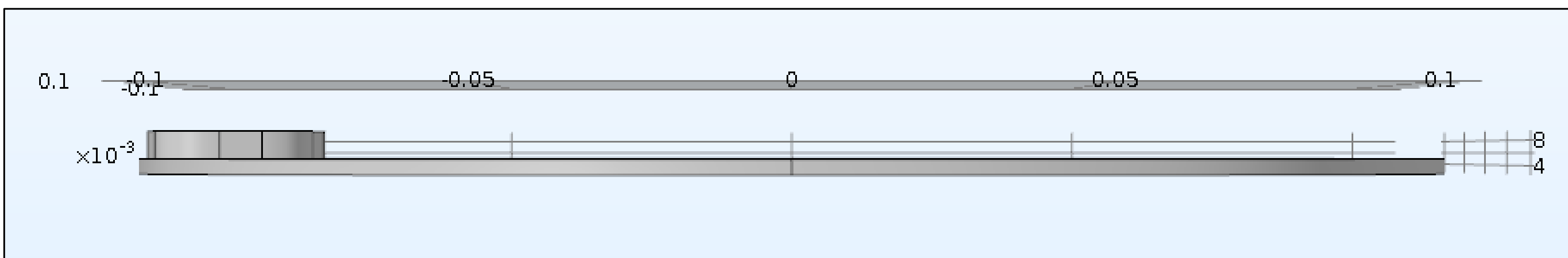
4. COMSOL 해석
-Reduction



4. COMSOL 해석
-Reduction

<COMSOL>

Half Model 사용

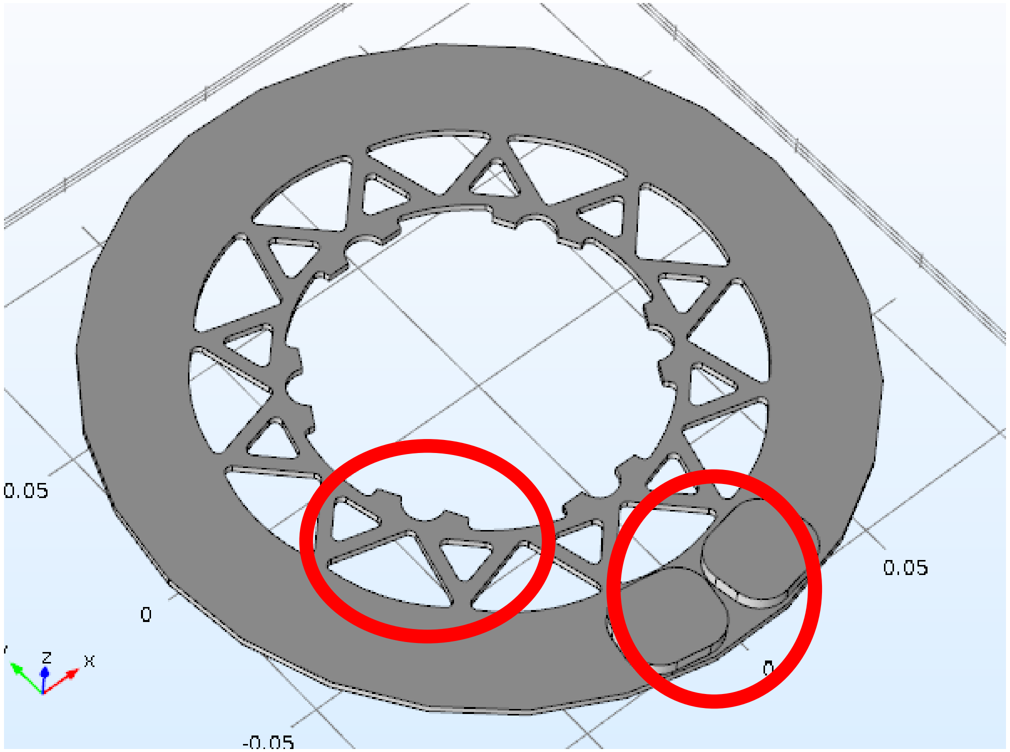


<Half Model>

4. COMSOL 해석
-Reduction

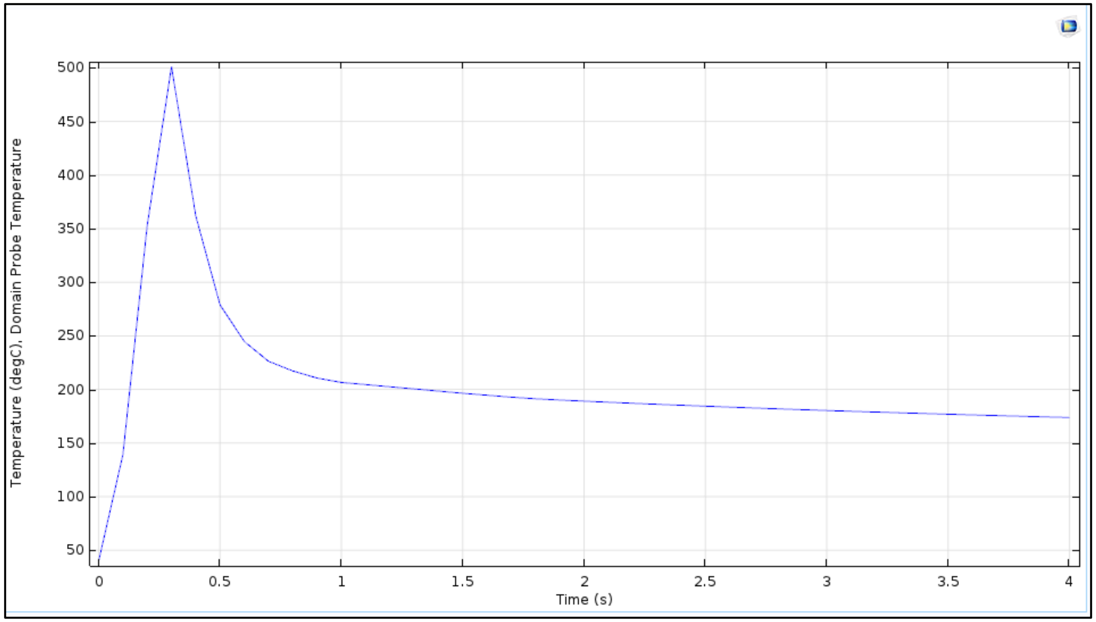
<COMSOL>

요소별 크기가 다른
Mesh 사용

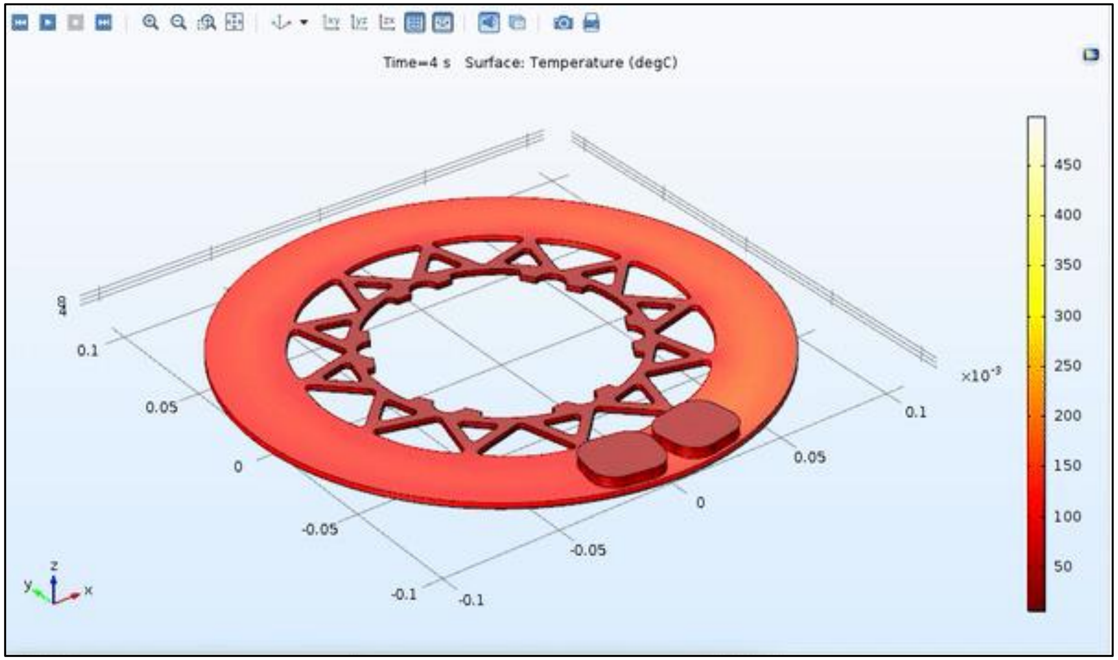


<u>Geometry 이슈 때문에 Mesh 생성 불가</u>

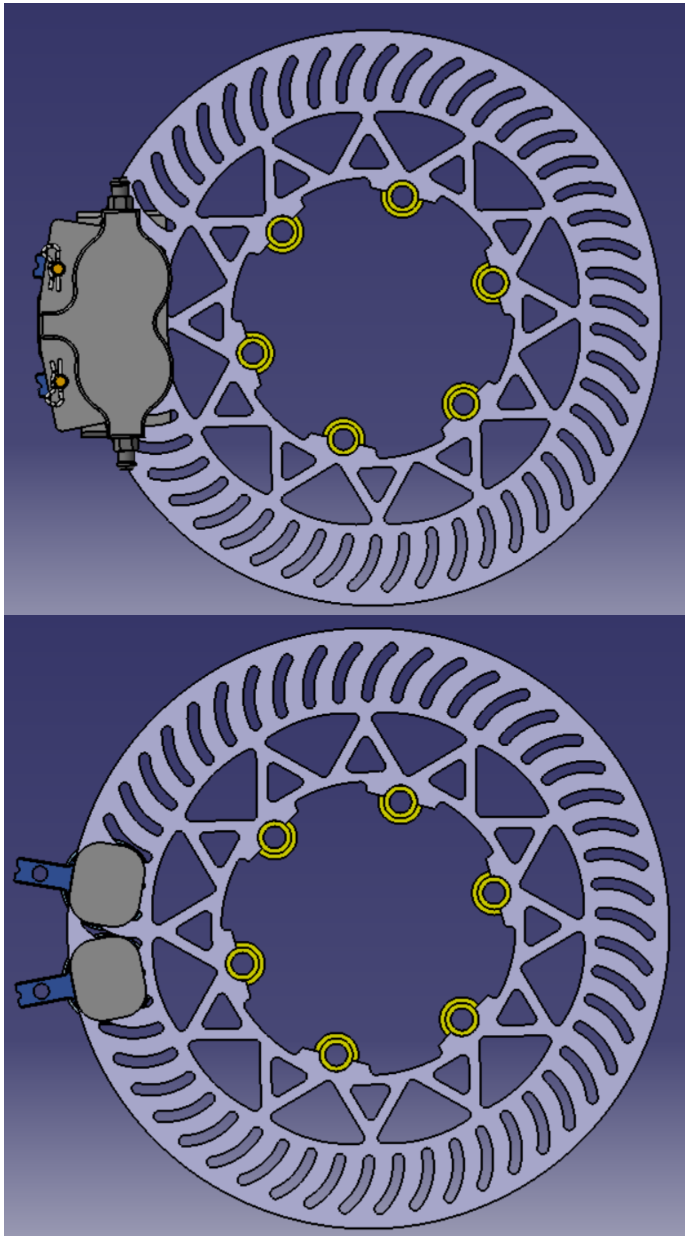
4. COMSOL 해석
-Result



Time (s)	Temperature (degC), Domain Probe Temperature
0.33600	493.65



4-1. Verification



실제 브레이크 형상

4-1. Verification

$$\theta_0(z,t)=\frac{q_0''}{h_R}\left[2\left(\frac{\theta_i h_R}{q_0''}-1\right)\sum_{n=1}^{\infty}\frac{\sin(\lambda_n L)}{\lambda_n L+\sin(\lambda_n L)\cos(\lambda_n L)}\times e^{-a_t\lambda_n^2 t}\cos(\lambda_n z)+1\right]$$

$a_t = \frac{k_R}{\rho_R c_R}$=thermal diffusivity
h_R = convective heat transfer coefficient
L = one-half rotor thickness
q_0''=average heat flux into rotor
t=time
T_i=initial temperature
T_∞=ambient temperature
z=horizontal distance measured from midplane to rotor
$\theta_0(z,t) = T_0(z,t) - T_\infty$
$\theta_i = T_i - T_a$=initial temperature difference between brake and ambient

$$(\lambda_n L)\tan(\lambda_n L) - \frac{h_R L}{k} = 0$$

The value of $\lambda_n L$ is determined from the transcendental equation.

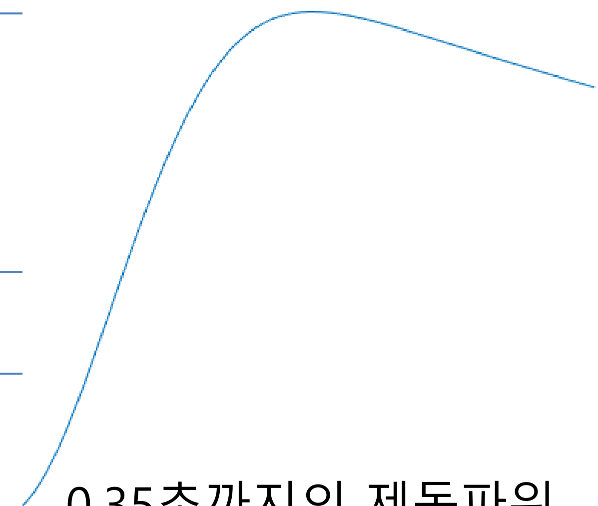
4-1. Verification

공기의 특성

- 밀도
- 동점성 계수

대류열전달 계수

- 레이놀즈 수 유도 -> 층류, 난류의 기준
- 층류: $h_R = 0.7\left(\frac{k_{air}}{D}\right)Re^{0.55}$
- 난류$(Re > 240000)$: $h_R = 0.4\left(\frac{k_{air}}{D}\right)Re^{0.8}$



0.35초까지의 제동파워

제동 파워

- $E_b = \frac{1}{2}mV^2 + \frac{1}{2}I\omega^2$
- $P_b = \frac{d(E_b)}{dt}$
- 락이 걸리기 전인 0.35초까지 제동파워를 구함
- 제동 파워 -> rms로 평균값 도출

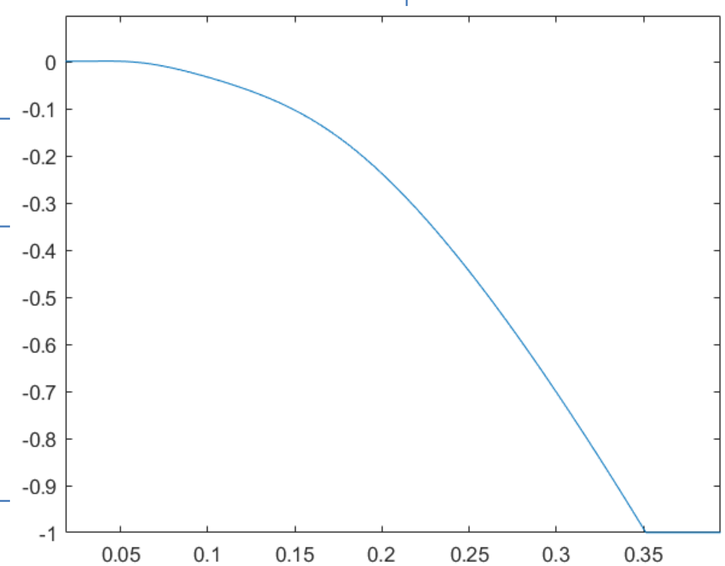
4-1. Verification

Heat flux 비율

- 디스크에 흡수되는 heat flux 비율
- $\gamma = \frac{1}{1+(\frac{\rho_P c_P k_P}{\rho_R c_R k_R})^{0.5}}$

Slip Ratio

- Slip ratio는 sin 함수의 형태를 나타냄
- Rms를 이용하여 평균값 도출



최종 온도

- 디스크 한쪽의 표면 온도
- 491℃

Time (s)	Temperature (degC), Domain Probe Temperature
0.33600	493.65

4-1. Verification

전체 코드

```
L = 2.5e-3;     % disc half thickness [m]
D = 217e-3;     % disc diameter [m]
%% air
alpha = readmatrix("air_alpha.csv");
c_p = readmatrix("air_capacity.csv");
rho_air = readmatrix("air_density.csv");
k_air = readmatrix("air_conductivity.csv");
mu = readmatrix("air_mu.csv");
nu = readmatrix("air_nu.csv");
Pr = readmatrix("air_Pr.csv");

%% Using air x = 36.11m/s to 0, y = 30 degrees celsius to 2000 degrees celcius
V = readmatrix("velocity_ms.csv");
V = linspace(V(1),V(end),1971); % vehicle velocity [m/s]
Re = rho_air.*V.*D./mu; % Reynolds number [1]

for i = 1:1971      % V = [36.11:0]
    for j = 1:1971  % T = [30:2000]
        if(Re(i,j) > 240000) % Turbulent flow
        h(j,i) = 0.4*(k_air(j)/D)*(Re(i,j)^0.8); % Convective heat transfer coefficient [W/(K*m^2)]

        else                 % Laminar flow
        h(j,i) = 0.7*(k_air(j)/D)*Re(i,j)^0.55;
        end
    end
end

%% Disc temperature analysis
k_R = 31;       % disc thermal conductivity [W/(m*K)]
t = 0.35;      % braking time [s]

Area = 752.25*4*10^(-6);
rho_rotor = 7600; % disc density [kg/m^3]
rho_pad = 2770;   % pad density [kg/m^3]
c_rotor = 460;    % specific heat of disc [J/(kg*K)]
c_pad = 1465;     % specific heat of pad [J/(kg*K)]
k_rotor = 31;     % thermal diffusivity of disc [W/(m*K)]
k_pad = 1.2116;   % thermal diffusivity of pad [W/(m*K)]

% ratio absorbs to disc
k = 1/(1 + ((rho_pad*c_pad*k_pad)/(rho_rotor*c_rotor*k_rotor))^0.5);



vehicle_braking_power = abs(readmatrix("power_temp.csv"));
vehicle_braking_power_cor=vehicle_braking_power(7:end);
slip = 0.4528; % slip ratio
brake_bias = 0.6;



Power = rms(vehicle_braking_power_cor)*brake_bias*0.25*k*(1 - slip);  % braking power [W]
q0 = Power/Area;% average heat flux [W/m^2]
init_temp = 40;             % Celcius
amb_temp = 40;
```

```
a_t = k_rotor./(rho_rotor*c_rotor); % thermal diffusivity
% lambda_1L = 0.2;
% lambda_1L = 0.4;
lambda_1L = 0.3566; % appiled by trial and error
% find out k1 = k2
k1 = lambda_1L*tan(lambda_1L);
k2 = h(1,11)*L / k_rotor;

if(abs(k1 - k2) < 0.001)
    theta = q0./h(1,11).*((2*((init_temp - amb_temp).*h(1,11)./q0 - 1)).*(sin(lambda_1L) ./ ...
    (lambda_1L + sin(lambda_1L).*cos(lambda_1L))).*exp(-a_t.*(lambda_1L./L).^2.*t).*cos(lambda_1L) + 1);
    temperature = theta + init_temp % final result
else
    disp('Cannot find the solution!');
end
```

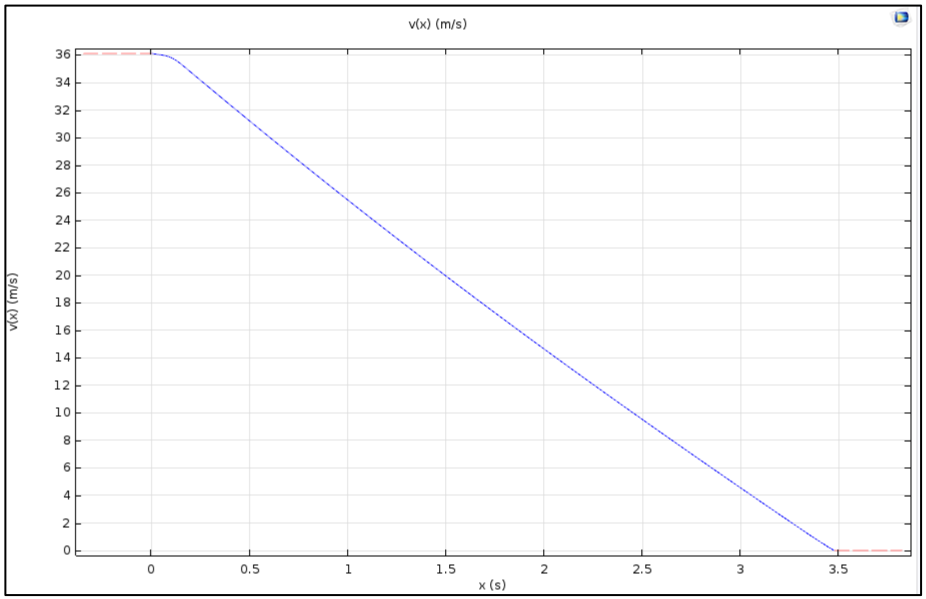
4. COMSOL 해석
-ABS Heat Analysis

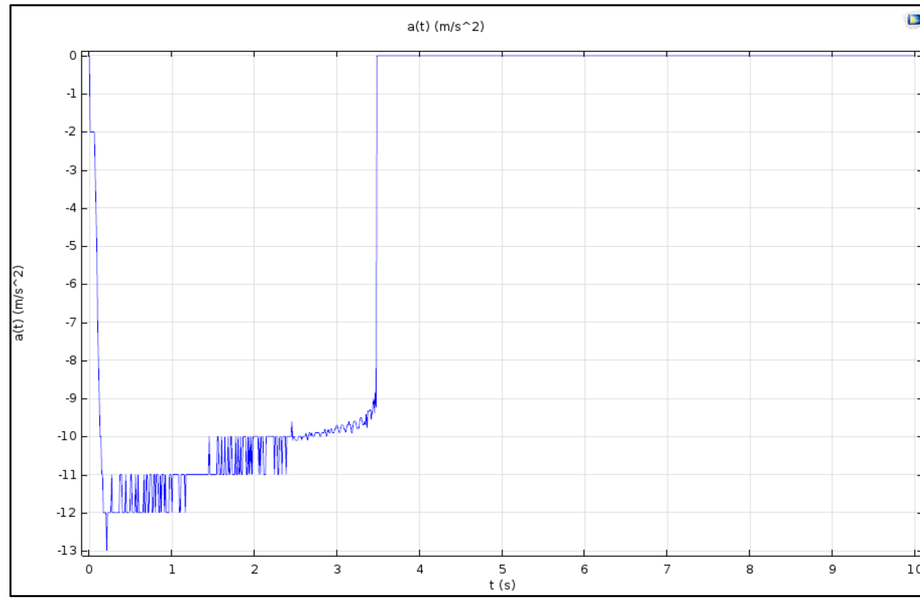
ABS

마찰되는 시간

온도

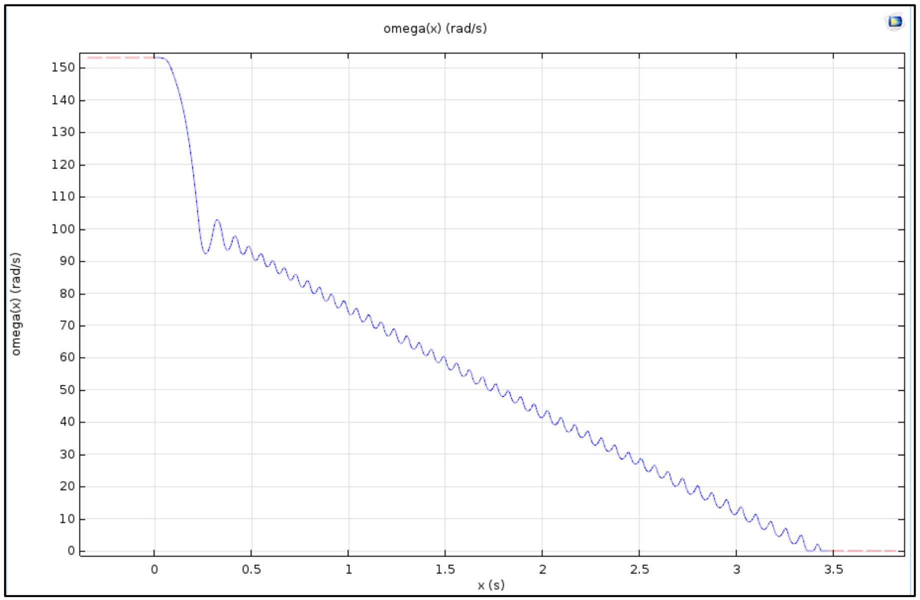
4. COMSOL 해석
-ABS Heat Analysis

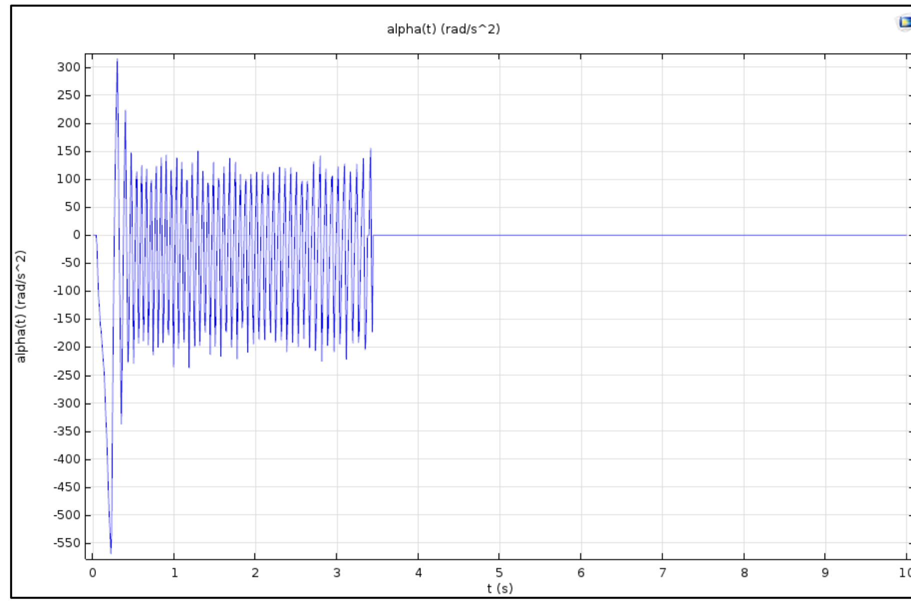




<Vehicle Velocity & Acceleration>

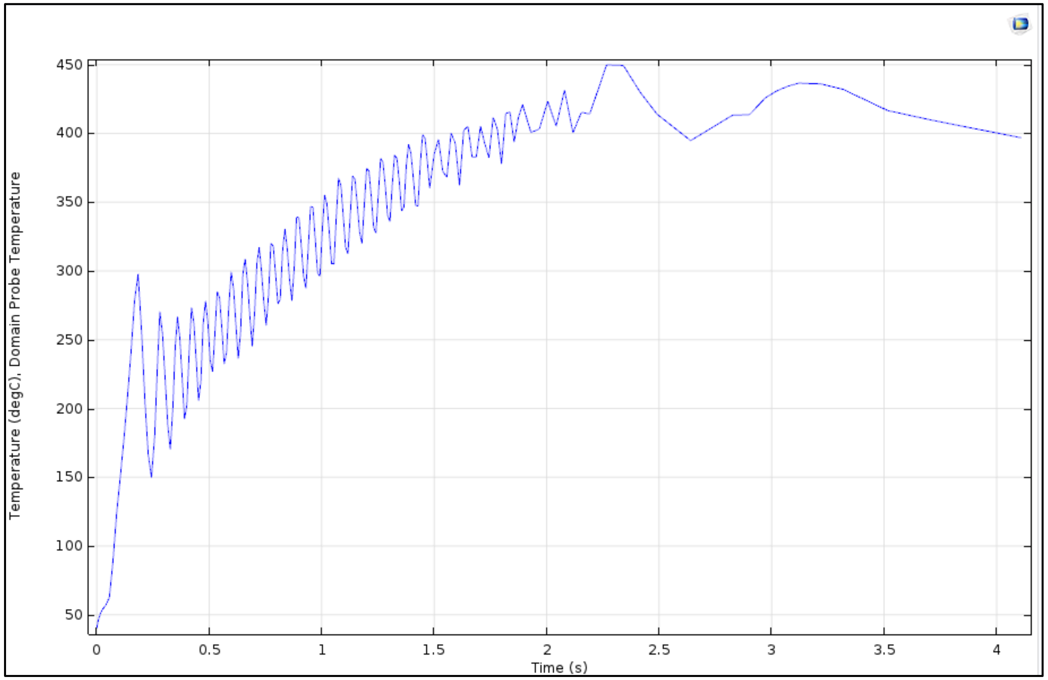
4. COMSOL 해석
-ABS Heat Analysis





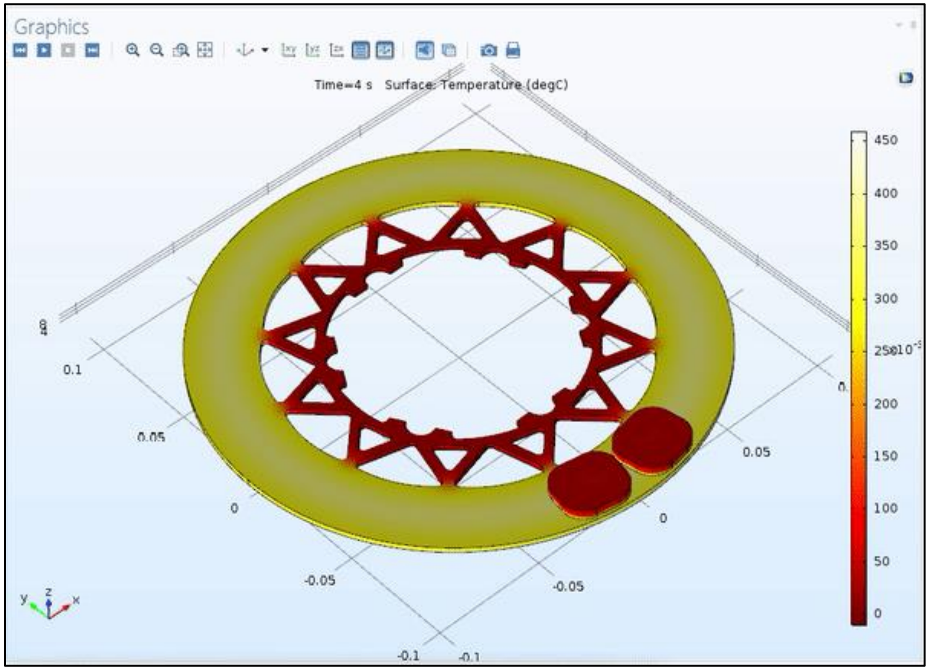
<Tire Angular Velocity & Acceleration>

4. COMSOL 해석
-ABS Heat Analysis



Time (s)	Temperature (degC), Domain Probe Temperature
2.2664	449.74

온도가 높은 상태로 지속되는 것을 볼 수 있음



4. COMSOL 해석
-ABS Heat Analysis

Solution

두께 증가

구멍 뚫기

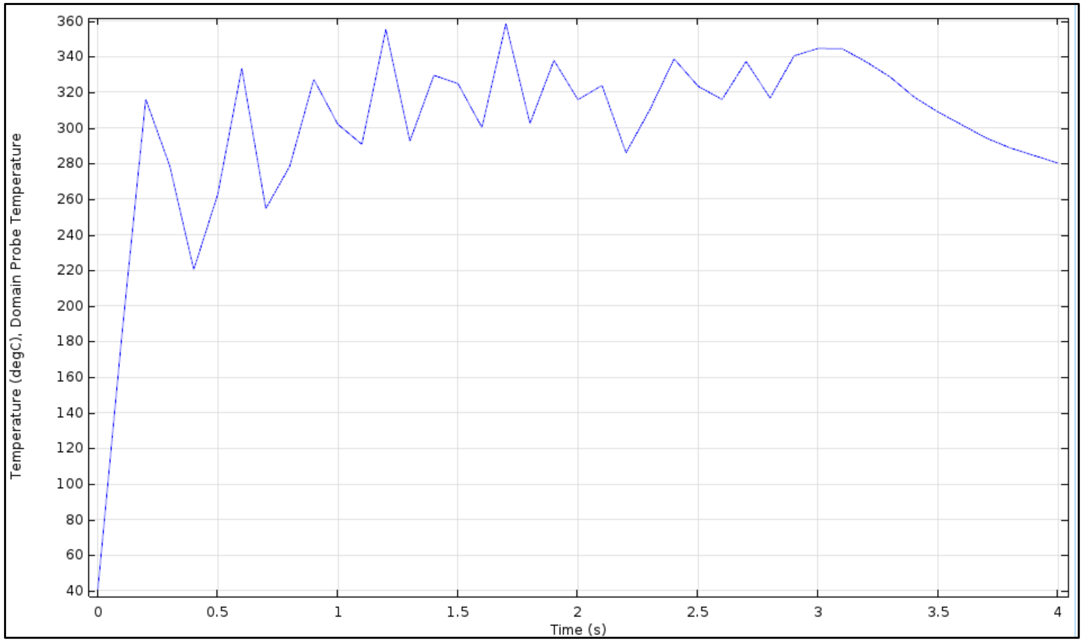
4. COMSOL 해석
-ABS Heat Analysis

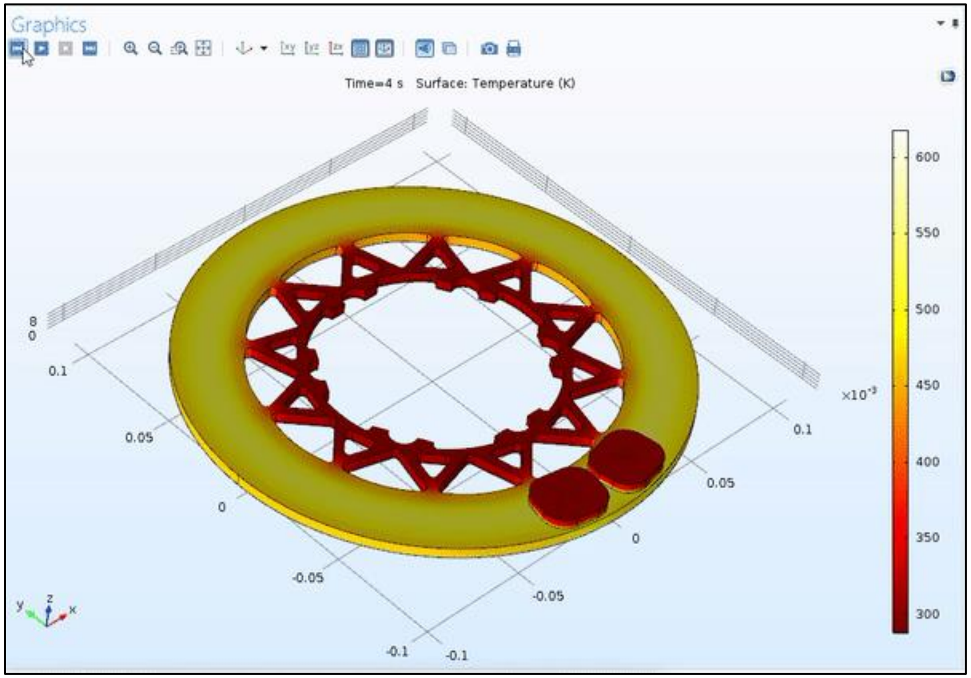
두께 증가

Time (s)	Temperature (degC), Domain Probe Temperature
2.2664	449.74

Time (s)	Temperature (degC), Domain Probe Temperature
1.7000	358.47

동일 주행 조건 하에서
두께 증가로 인해 ***최대 온도 감소***





4. COMSOL 해석
-ABS Heat Analysis

구멍 뚫기

<u>Comsol에서 Mesh를 만들지 못해서 불가</u>

5. Conclusion

1. ABS 사용 시, 동일 초기 속도에서 제동거리가 감소하는 것을 확인

2. Disc의 두께를 증가시킬 경우, Disc의 최대 온도가 감소하는 것을 확인

* Reference

1. Brake Design and Safety – Rudolf Limpert (SAE International)

2. Heat and Mass Transfer – Yunus A. Cengel

3. Heat Transfer Module Users Guide – COMSOL

4. Step by step guide for modeling heat generation in a disc brake - COMSOL

Q & A