차량의 연비 및 성능 향상을 위한 감속기의 기어 요소 및 오일량 최적화

팀명 : 감.자.맨 (감속기를 자체해석하는 남자들)

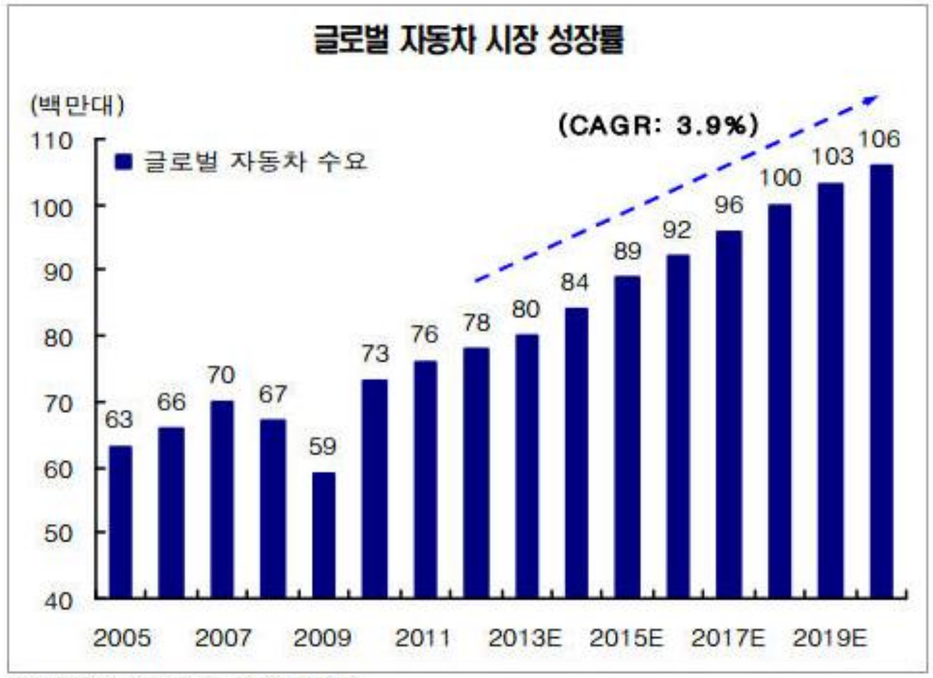
팀원 : 한국기술교육대학교 박지원, 한국기술교육대학교 김호진

지도교수 : 정승현 교수님

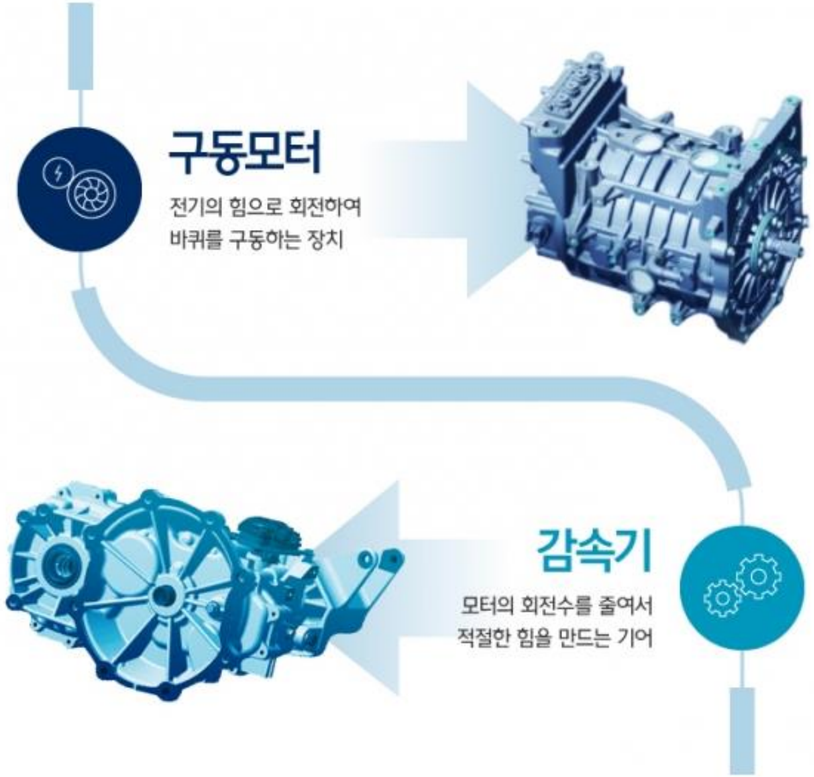
0. background

➢ 연구배경

- *자동차의 시장 규모가 증가함에 따라, 차량의 성능과 연비를 개선하기 위해 감속기에 대한 연구 확대*
- *감속기는 모터에서 타이어까지의 토크를 증가시키는 역할을 함*
- *감속기의 온도는 모터의 성능까지 영향을 끼침*



자료: Global Insight, KB투자증권

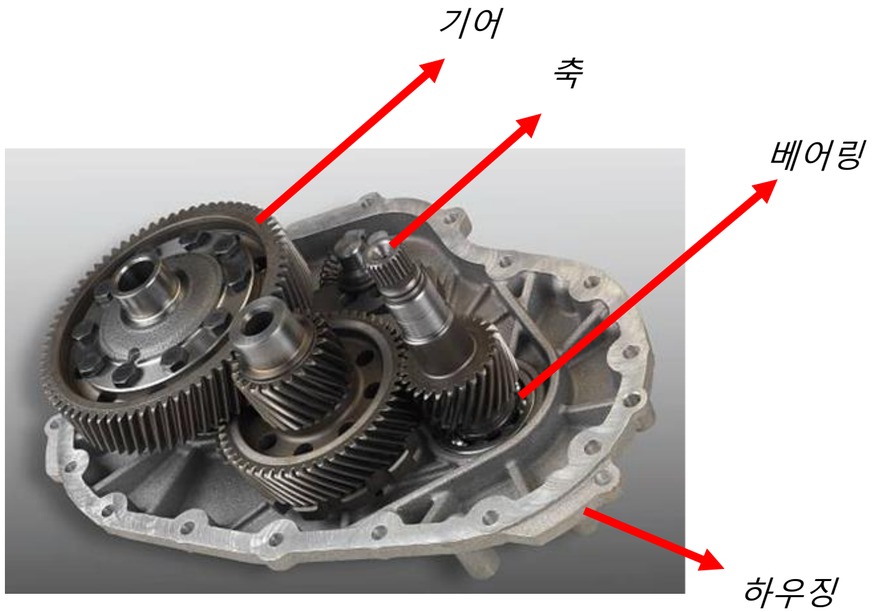


0. background

➢ 감속기 구조

- *감속기는 크게 기어, 축, 베어링, 하우징 부분으로 나눌수 있음*
- *헬리켈기어는 감속기의 효율을 증가시키고, 강성 감소 효과 가짐*
- *스러스트 베어링은 감속기의 축하중을 부담 감소*

  -> 따라서 본 연구에서 헬리켈 기어와 스러스트 베어링이 내장된 감속기 해석



< Gearbox 구조 >

평기어

볼베어링

헬리컬 기어

스러스트 베어링

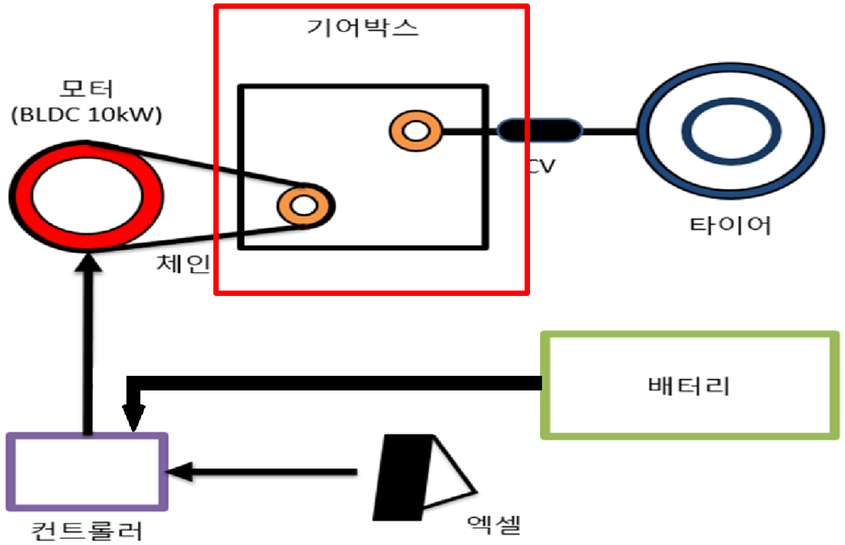
0. background

➢ 모터 선정 및 구동계

• *48V 10kW BLDC Motor 선정*

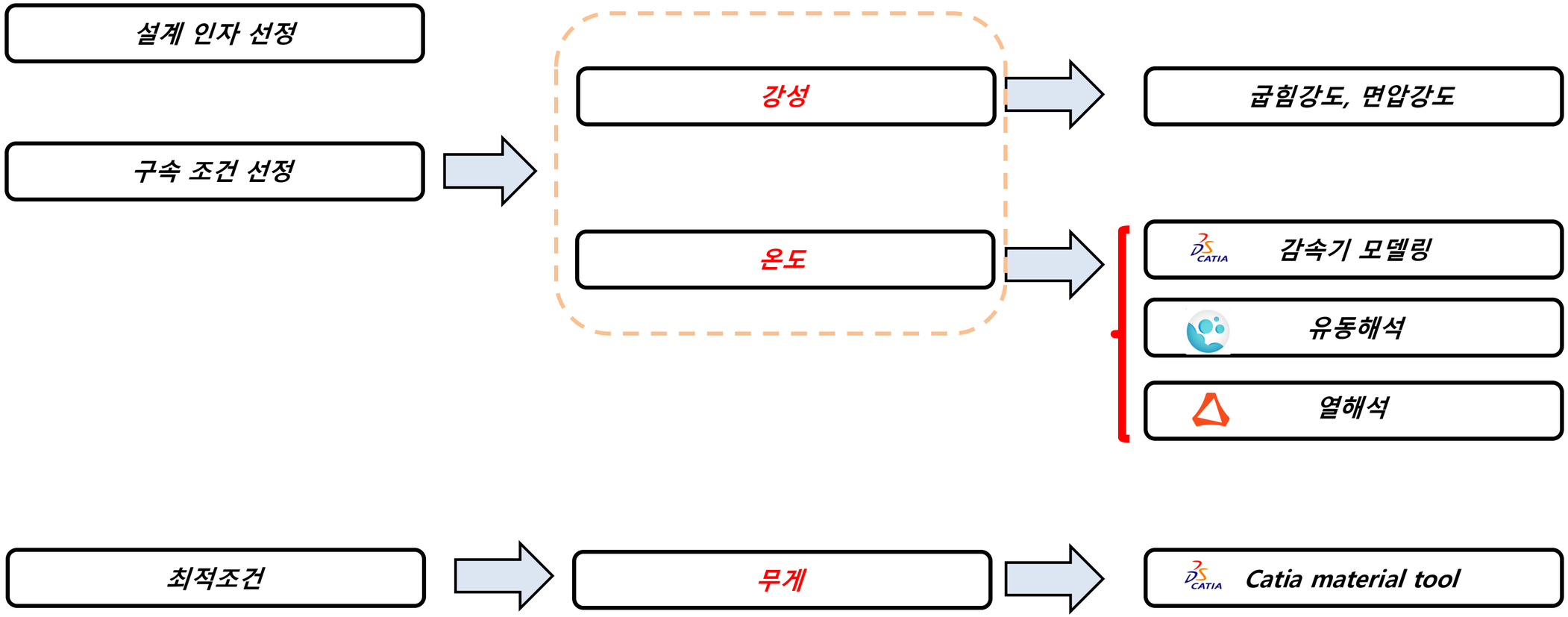
- **Golden motor**

- 3상 BLDC모터
- 제품명 : GOLDEN MOTOR
- Rated Power[W] : 10,000
- Rated Voltage[V] : 48
- Rated Current[A] : 250
- Rated Torque[Nm] : 26
- Rated Rotate[RPM] : 3500
- 절연등급 : H
- Cooling : Liquid
- 가격 : 1,800,000 원



0. background

➢ 최적화 과정



01. 설계인자선정

➢ 실험계획법 -직교배열표

- *직교배열표를 사용하여 최적화 문제 해결*
- *4인자 3수준으로 설정*
- *무게와 강성에 영향을 미치는 모듈,아나비, 비틀림각과 온도에 영향을 미치는 오일 level을 인자로 선정*
- *모듈, 이나비, 비틀림각에 따라 하우징의 크기도 변화*

$$\text{최소실험 횟수} = \frac{(\text{인자수}+1)(\text{인자수}+2)}{2}$$

$$= \frac{(4+1)(4+2)}{2}$$

$$= 15$$

Case	모듈 (mm)	이나비 (mm)	비틀림각 (°)	오일 level
1	2	10	10	Low
2	2	15	15	Mid
3	2	20	20	High
4	2.5	10	15	High
5	2.5	15	20	Low
6	2.5	20	10	Mid
7	3	10	20	Mid
8	3	15	10	High
9	3	20	15	Low
10	2	10	15	High
11	2	15	10	Low
12	2.5	20	20	Mid
13	2.5	10	10	Low
14	3	15	15	Mid
15	3	20	20	High

01. 설계인자선정

➢ 실험계획법 - 최적조건

- *최적조건 -> 기어박스의 무게 (경량화)*
- *목적함수를 구하여 기어박스의 무게 최적화*
- *구속조건에 해당하는 값은 제외*
- *목적함수는 Full Quadratic Polynomial Model 사용*

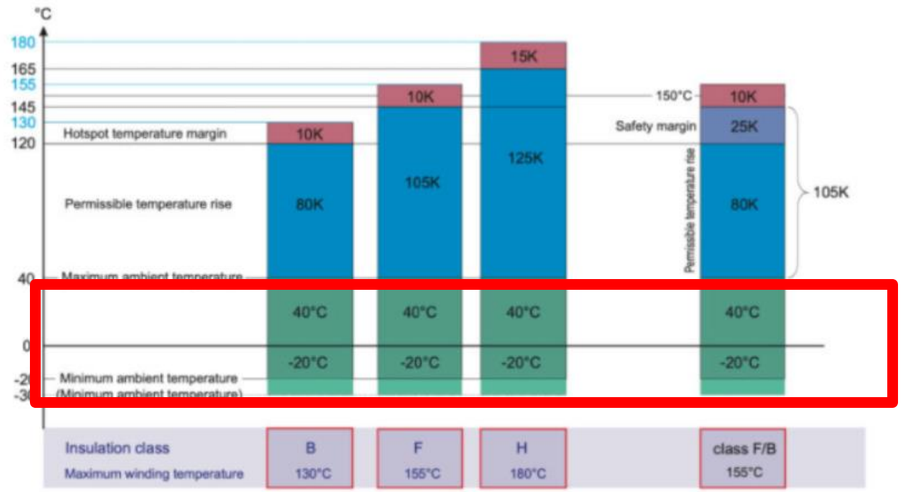
4인자일때 *목적함수*

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4$$

02. 구속조건

➢ 실험계획법 – 구속조건 선정

경계조건1. 하우징의 최대온도 < 40도



< 모터의 온도 상승 그래프 >

경계조건2. 기어박스의 허용전달동력 > 10kW

- **Golden motor**

- 3상 BLDC모터
- 제품명 : GOLDEN MOTOR
- Rated Power[W] : 10,000
- Rated Voltage[V] : 48
- Rated Current[A] : 250
- Rated Torque[Nm] : 26
- Rated Rotate[RPM] : 3500
- 절연등급 : H
- Cooling : Liquid
- 가격 : 1,800,000 원

< Golden Motor 스펙>

02. 강성 확인

➢ 강성확인을 위한 허용전달동력

- *굽힘강도와 면압강도의 각 기어의 허용전달동력을 구함*
- *가장 낮은 허용전달동력을 기준으로 구속조건을 설정함*

경계조건2. 기어박스의 허용전달동력 > 10kW

- **Golden motor**

- 3상 BLDC모터
- 제품명 : GOLDEN MOTOR
- Rated Power[W] : 10,000
- Rated Voltage[V] : 48
- Rated Current[A] : 250
- Rated Torque[Nm] : 26
- Rated Rotate[RPM] : 3500
- 절연등급 : H
- Cooling : Liquid
- 가격 : 1,800,000 원

< Golden Motor 스펙>

경계조건 식 도출

<굽힘 강도>

$$F_n = f_v f_w \sigma_b m_n b y_\epsilon$$

F_n : 허용 회전력 $[N]$

f_v : 속도계수

f_w : 하중계수

σ_b : 허용 굽힘응력 $[Mpa]$

m_n : 치직각 모듈 $[mm]$

b : 이나비 $[mm]$

y_ϵ : 치형계수

$$v[m/s] = \frac{\pi DN}{60 \times 1000}$$

원주속도 : v $[m/s]$

축직각 피치원 지름 : D $[mm]$

회전속도 : N $[rpm]$

$$\therefore H_a = \frac{Fv}{1000} \ [kW]$$

허용전달동력 : H $[kW]$

회전력 : F $[N]$

원주속도 : v $[m/s]$

<면압 강도>

$$F = f_v \frac{C_w}{\cos^2(\beta)} k b m_z \frac{2 z_1 z_2}{z_1 + z_2}$$

F : 회전력 $[N]$

f_v : 속도계수

C_w : 면압계수

β : 비틀림각 $[^\circ]$

k : 접촉면 응력계수 $[N/mm^2]$

b : 축직각 단면의 이나비 $[mm]$

m_z : 축직각 모듈 $[mm]$

z_1 : 피니언 기어

z_2 : 기어

02. 강성 확인

➢ 강성확인을 위한 허용전달동력

- *굽힘강도와 면압강도 공식을 바탕으로 경계조건에 해당하는 모델 선정*
- *경계조건에 해당하는 총 8개 모델 도출*

기어박스의 허용전달동력 > 10kW

- **Golden motor**

- 3상 BLDC모터
- 제품명 : GOLDEN MOTOR
- Rated Power[W] : 10,000
- Rated Voltage[V] : 48
- Rated Current[A] : 250
- Rated Torque[Nm] : 26
- Rated Rotate[RPM] : 3500
- 절연등급 : H
- Cooling : Liquid
- 가격 : 1,800,000 원

< Golden Motor 스펙>

경계 조건을 만족하는 모델

해석순서	모듈	이나비	비틀림각	오일 level	강성(kW)
1	*3.5*	*25*	*10*	*30*	*15.79825*
2	*3.5*	*15*	*15*	*60*	*9.47895*
3	*3.5*	*20*	*20*	*90*	*12.6386*
4	*2.5*	*25*	*15*	*90*	*10.0043*
5	*2.5*	*15*	*20*	*30*	*6.00262*
6	*2.5*	*20*	*10*	*60*	*8.00349*
7	*3*	*25*	*20*	*60*	*12.85595*
8	*3*	*15*	*10*	*90*	*7.71357*
9	*3*	*20*	*15*	*30*	*10.284764*
10	*3.5*	*25*	*15*	*90*	*15.79825*
11	*3.5*	*15*	*10*	*30*	*9.47895*
12	*2.5*	*20*	*20*	*60*	*8.00349*
13	*2.5*	*25*	*10*	*30*	*10.0043*
14	*3*	*15*	*15*	*60*	*7.71357*
15	*3*	*20*	*20*	*90*	*10.28476*

<굽힘 강도>

$$F_t = f_v f_w \sigma_b m_n b y_t$$

F_t : 허용 회전력 $[N]$
f_v : 속도계수
f_w : 하중계수
σ_b : 허용 굽힘응력 $[Mpa]$
m_n : 치직각 모듈 $[mm]$
b : 이나비 $[mm]$
y_t : 치형계수

$$v[m/s] = \frac{\pi DN}{60 \times 1000}$$

원주속도 : v $[m/s]$
축직각 피치원 지름 : D $[mm]$
회전속도 : N $[rpm]$

$$\therefore H_n = \frac{Fv}{1000} \ [kW]$$

허용전달동력 : H $[kW]$
회전력 : F $[N]$
원주속도 : v $[m/s]$

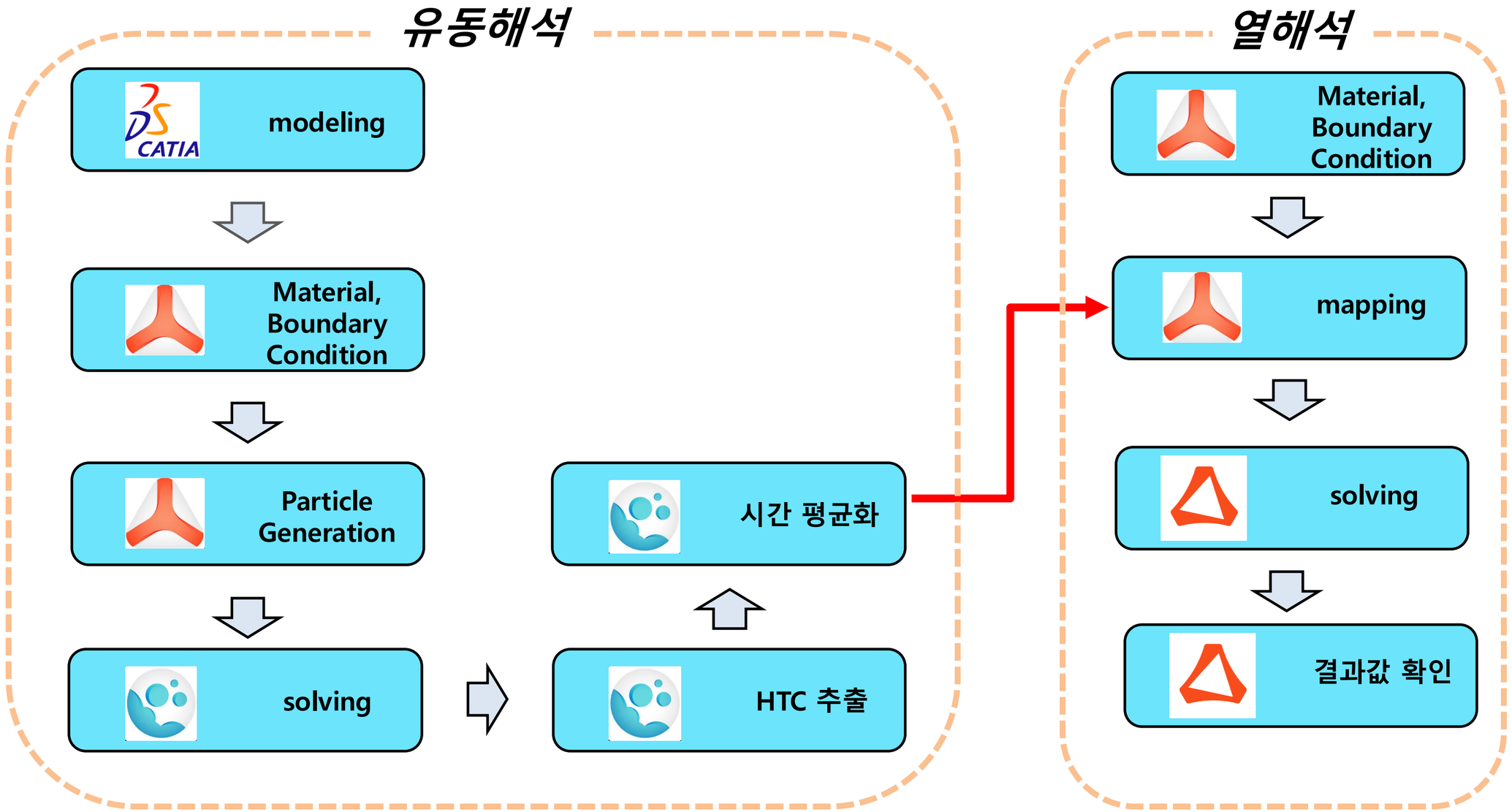
<면압 강도>

$$F = f_v \frac{C_w}{\cos^2(\beta)} k b m_z \frac{2z_1 z_2}{z_1 + z_2}$$

F : 회전력 $[N]$
f_v : 속도계수
C_w : 면압계수
β : 비틀림각 $[^\circ]$
k : 접촉면 응력계수 $[N/mm^2]$
b : 축직각 단면의 이나비 $[mm]$
m_z : 축직각 모듈 $[mm]$
z_1 : 피니언 기어
z_2 : 기어

03. 열유체 해석

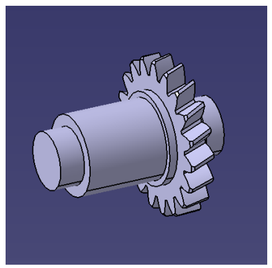
➢ 감속기의 열유체 해석 프로세스



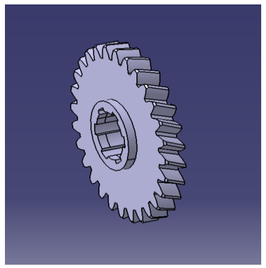
03. 열유체 해석

➢ Catia를 이용한 기어박스 모델링

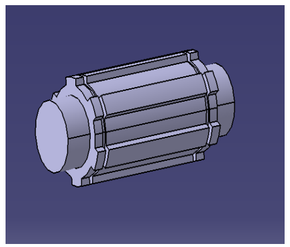
- *gear, sharft, bearing, housing을 모델링하고 gearbox로 assembly 실시*



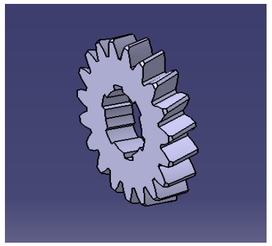
Input gear



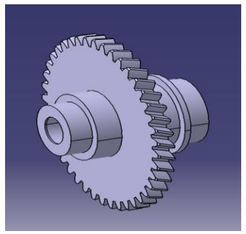
Mid1 gear



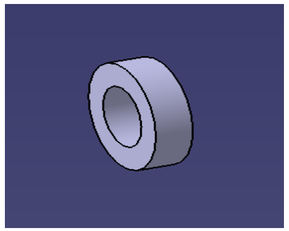
Shaft



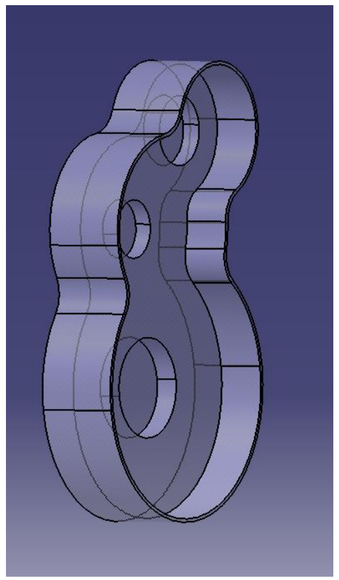
Mid2 gear



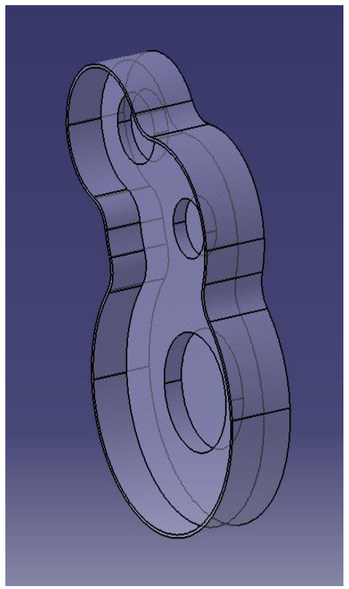
Output gear



bearing

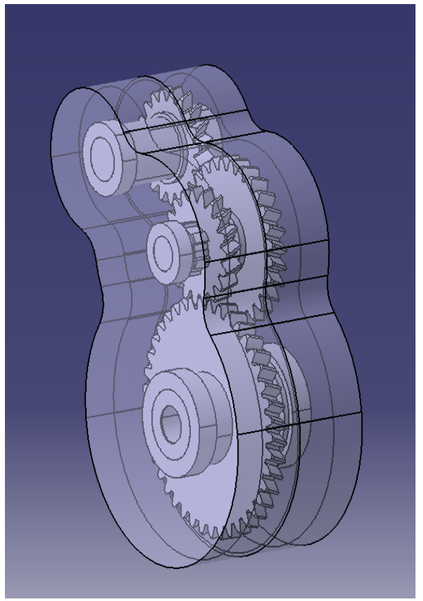


Housing_L



Housing_R

Assembly



기어박스
최종형상

03. 열유체 해석

➢ 재료선정

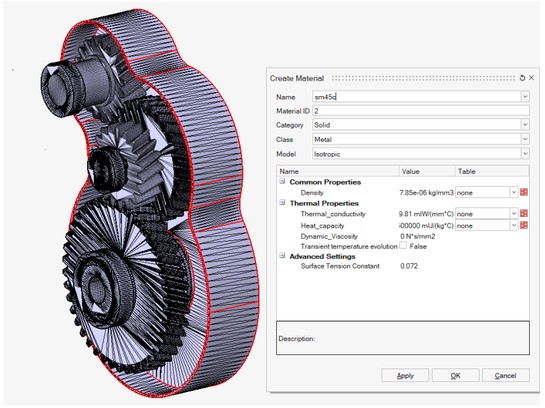
- *각 부품에 아래 표와 같이 재료선정*

	Material	Density [kg/m^3]	Poisson's ratio	Thermal expansion coefficient [k^-1]	Yield stress [Mpa]	Thermal conductivity [W/(m*K)]	Heat capacity [J/(kg*K)]
Gear	*sm45c*	*7850*	*0.29*	*11.7 X 10^-6*	*305*	*45*	*460*
Shaft	*sm45c*	*7850*	*0.29*	*11.7 X 10^-6*	*305*	*45*	*460*
Bearing	*sus440c*	*7700*	*0.27*	*10.8 X 10^-6*	*1000*	*24*	*460*
housing	*al6061*	*2700*	*0.33*	*23.6 X 10^-6*	*276*	*167*	*900*

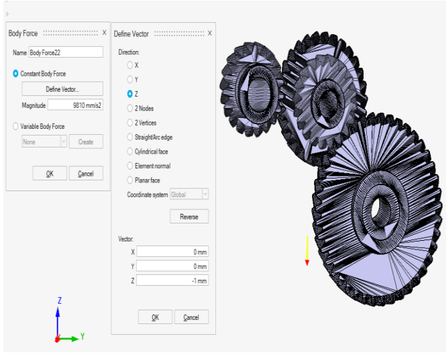
03. 열유체 해석

➢ 재료할당 및 입자생성

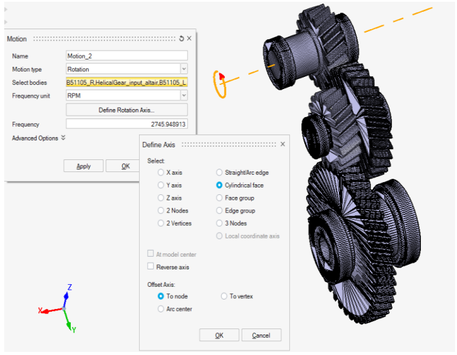
- *모델을 Altair에 불러와 재료 할당, 경계조건 입력 및 입자 생성*



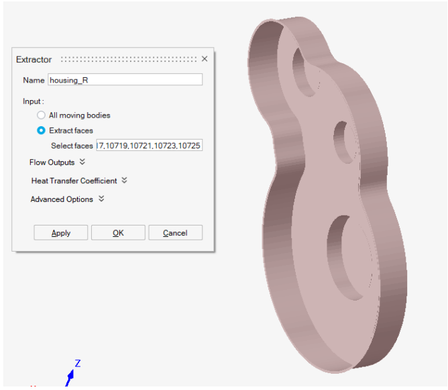
<재료할당>



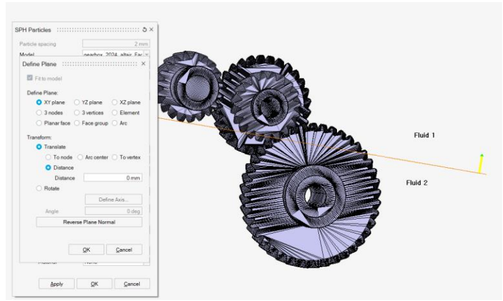
<Body Force>

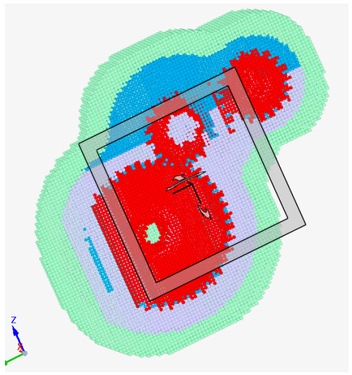


<Motion>



<Extractor>





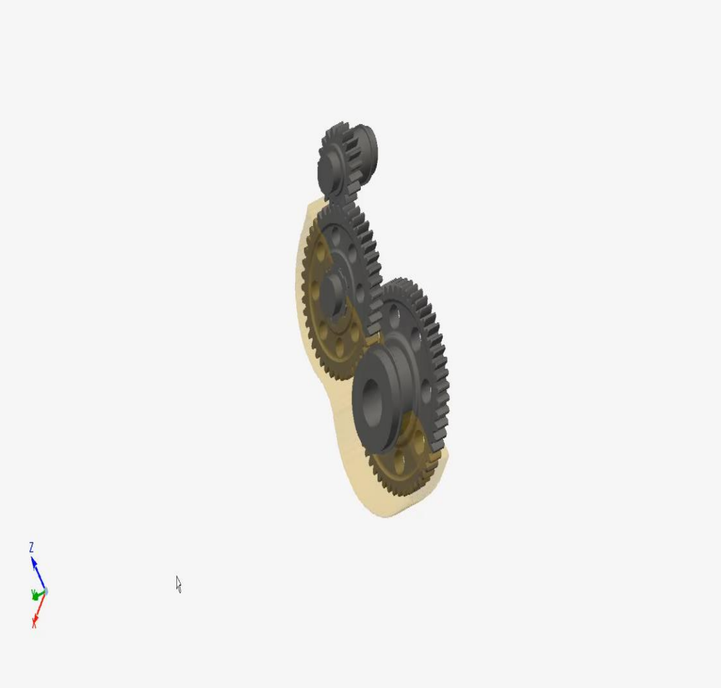
<Particle Generation>

오일 level
Low : XY 평면으로부터 -30mm 까지의 오일 높이
Mid : XY 평면에서의 오일 높이
High : XY 평면으로부터 +30mm 까지의 오일 높이

03. 열유체 해석

➢ HTC 추출

- *입자 생성후 HTC값 추출*



surfext_0.txt 2024-05-13 오후 2:20 텍스트 문서
surfext_10137.txt 2024-05-13 오후 2:21 텍스트 문서
surfext_20274.txt 2024-05-13 오후 2:22 텍스트 문서
surfext_30411.txt 2024-05-13 오후 2:23 텍스트 문서
surfext_40548.txt 2024-05-13 오후 2:24 텍스트 문서
surfext_50685.txt 2024-05-13 오후 2:25 텍스트 문서
surfext_60822.txt 2024-05-13 오후 2:26 텍스트 문서
surfext_70959.txt 2024-05-13 오후 2:28 텍스트 문서
surfext_81095.txt 2024-05-13 오후 2:29 텍스트 문서
surfext_91232.txt 2024-05-13 오후 2:30 텍스트 문서
surfext_101369.txt 2024-05-13 오후 2:31 텍스트 문서
surfext_111506.txt 2024-05-13 오후 2:32 텍스트 문서
surfext_121643.txt 2024-05-13 오후 2:33 텍스트 문서
surfext_131780.txt 2024-05-13 오후 2:35 텍스트 문서
surfext_141917.txt 2024-05-13 오후 2:36 텍스트 문서
surfext_152054.txt 2024-05-13 오후 2:37 텍스트 문서
surfext_162190.txt 2024-05-13 오후 2:38 텍스트 문서
surfext_162191.txt 2024-05-13 오후 2:38 텍스트 문서
surfext_172327.txt 2024-05-13 오후 2:39 텍스트 문서
surfext_182464.txt 2024-05-13 오후 2:40 텍스트 문서
surfext_192601.txt 2024-05-13 오후 2:42 텍스트 문서
surfext_202738.txt 2024-05-13 오후 2:43 텍스트 문서
surfext_212875.txt 2024-05-13 오후 2:44 텍스트 문서
surfext_223012.txt 2024-05-13 오후 2:45 텍스트 문서
surfext_233149.txt 2024-05-13 오후 2:46 텍스트 문서
surfext_243285.txt 2024-05-13 오후 2:47 텍스트 문서
surfext_253422.txt 2024-05-13 오후 2:48 텍스트 문서
surfext_263559.txt 2024-05-13 오후 2:50 텍스트 문서
surfext_273696.txt 2024-05-13 오후 2:51 텍스트 문서
surfext_283833.txt 2024-05-13 오후 2:52 텍스트 문서

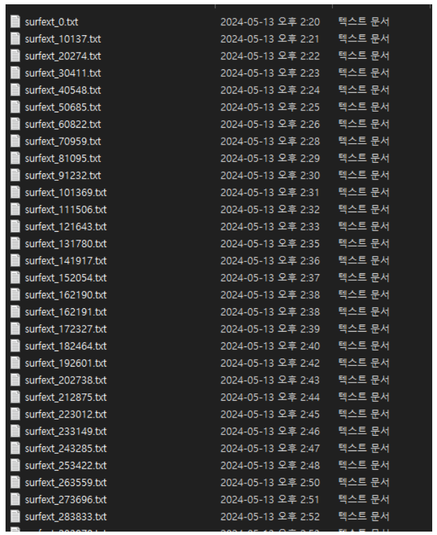
X	Y	Z	HTC
-0.410546	-0.0352048	0.044987	0.290941
-0.414091	-0.0362189	0.0454567	1.21814
-0.410338	-0.0363969	0.0463604	0.508754
-0.413877	-0.0374499	0.0467943	1.2383
-0.410111	-0.0377023	0.0476231	0.604609
-0.413643	-0.038791	0.048018	1.1319
-0.409865	-0.0391113	0.0487656	0.53451
-0.413392	-0.0402321	0.0491183	0.895574
-0.409603	-0.0406129	0.049779	0.50859
-0.413125	-0.0417622	0.050087	0.750736
-0.409327	-0.0421959	0.0506557	0.602261
-0.412845	-0.0433696	0.0509166	1.08899
-0.409039	-0.0438481	0.0513891	0.753009
-0.412553	-0.0450422	0.0516008	1.79248
-0.408741	-0.045557	0.0519735	0.8149
-0.412252	-0.0467671	0.0521344	2.73555
-0.408436	-0.0473096	0.0524044	0.823878
-0.411945	-0.0485313	0.0525135	3.3185
-0.408125	-0.0490925	0.0526787	0.919307
-0.411633	-0.0503213	0.052735	3.16986

03. 열유체 해석

➢ 입자데이터 보간 및 시간 평균화

- *입자데이터 보간 및 시간 평균화를 통한 Temperature 도출*

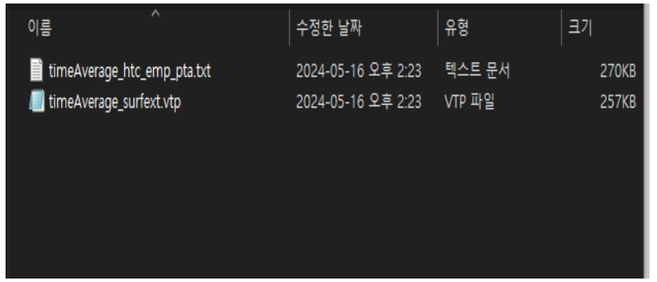
NanoFluidX를 이용하여
x,y,z HTC 값 추출



Nfx를 이용한
입자 데이터 보간 및 시간 평균화

```
PS C:₩Users₩KITECH₩Documents> cd C:₩Users₩KITECH₩Desktop₩DrivetrainOiling_2
PS C:₩Users₩KITECH₩Desktop₩DrivetrainOiling_2> nFXc --nfx DrivetrainOiling.cfg

-------------------------------------------------
||| Altair nanoFluidX(TM)                2023.1 |||
|||-----------------------------------------------|||
||| nanoFluidX companion                 2023.1 |||
||| nFX[c]                         20231018.e12aa8c |||
-------------------------------------------------

Operating in nFX interpolation mode.

Interpolating in standalone mode.
Simulation start time: 0 (s)
Simulation end time:   5 (s)
Averaging start time: 0.1 (s)
Averaging end time:   1 (s)

Number of nFX output particles: 24083
Number of interpolation points: 173280 at 57x38x80

Reading particle data from particles_0.pvtu
>> save file :: simulation time :: expected time :: average time
>> 0/100 :: 0/5 :: 0.239702/24.2099 :: 0.239702/0.239702

Reading particle data from particles_10137.pvtu
>> 1/100 :: 0.0500006/5 :: 0.545192/27.5322 :: 0.30549/0.272596

Reading particle data from particles_20274.pvtu
Starting time averaging ...
```

Temperatur 추출



03. 열유체 해석

➢ CSV file 변환 및 HTC 가시화

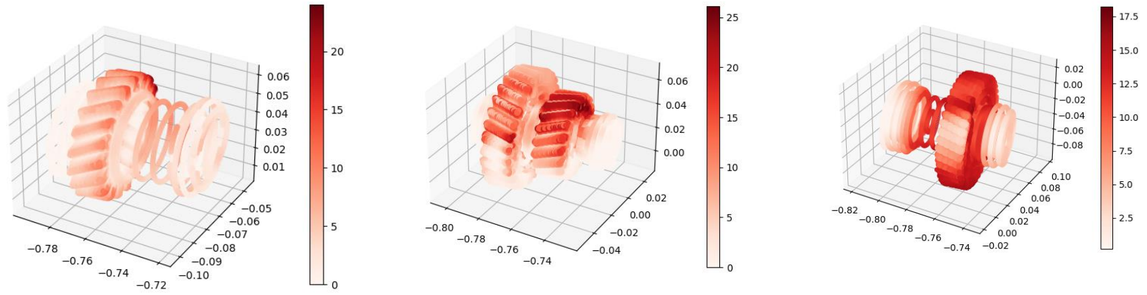
- *엑셀을 이용하여 text 파일을 csv파일로 변환후 python으로 가시화*
- *가시화 실시 결과 HTC가 오일의 level에 따라 다르게 분포하는것을 볼 수 있음*

Text file

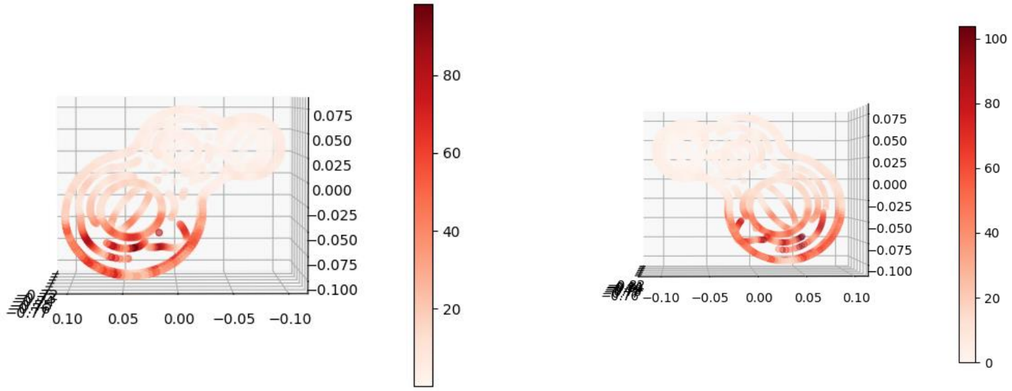
```
-0.410546 -0.0352048 0.044987 0.290941
-0.414091 -0.0362189 0.0454567 1.21814
-0.410338 -0.0363969 0.0463604 0.508754
-0.413877 -0.0374499 0.0467943 1.2383
-0.410111 -0.0377023 0.0476231 0.604609
-0.413643 -0.038791 0.048018 1.1319
-0.409865 -0.0391113 0.0487656 0.53451
-0.413392 -0.0402321 0.0491183 0.895574
-0.409603 -0.0406129 0.049779 0.50859
-0.413125 -0.0417622 0.050087 0.750736
-0.409327 -0.0421959 0.0506557 0.602261
-0.412845 -0.0433696 0.0509166 1.08899
-0.409039 -0.0438481 0.0513891 0.753009
-0.412553 -0.0450422 0.0516008 1.79248
-0.408741 -0.045557 0.0519735 0.8149
-0.412252 -0.0467671 0.0521344 2.73555
-0.408436 -0.0473096 0.0524044 0.823878
-0.411945 -0.0485313 0.0525135 3.3185
-0.408125 -0.0490925 0.0526787 0.919307
-0.411633 -0.0503213 0.052735 3.16986
```

CSV file

X	Y	Z	Temperatu	HTC
-0.41055	-0.0352	0.044987	300	53.8637
-0.41409	-0.03622	0.045457	300	101.196
-0.41034	-0.0364	0.04636	300	54.406
-0.41388	-0.03745	0.046794	300	100.676
-0.41011	-0.0377	0.047623	300	53.5291
-0.41364	-0.03879	0.048018	300	97.8763
-0.40987	-0.03911	0.048766	300	51.4175
-0.41339	-0.04023	0.049118	300	92.8147
-0.4096	-0.04061	0.049779	300	49.1143
-0.41313	-0.04176	0.050087	300	88.3929
-0.40933	-0.0422	0.050656	300	48.4363
-0.41285	-0.04337	0.050917	300	88.8908
-0.40904	-0.04385	0.051389	300	51.7016
-0.41255	-0.04504	0.051601	300	96.1726
-0.40874	-0.04556	0.051974	300	59.693
-0.41225	-0.04677	0.052134	300	108.291
-0.40844	-0.04731	0.052404	300	71.0101
-0.41195	-0.04853	0.052514	300	121.41
-0.40813	-0.04909	0.052679	300	83.2004



input mid output



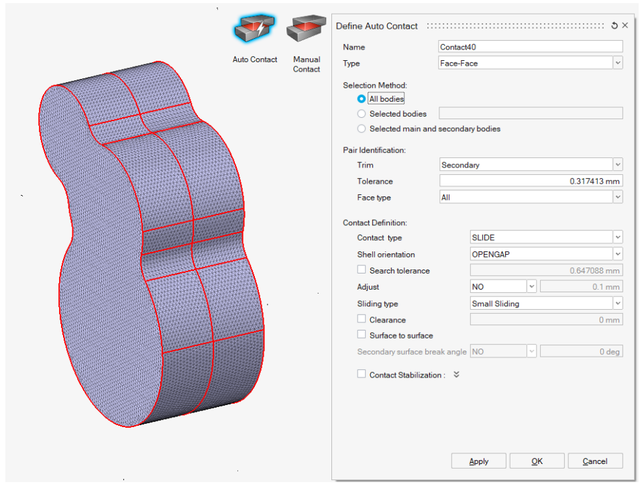
Housing_L Housing_R

03. 열유체 해석

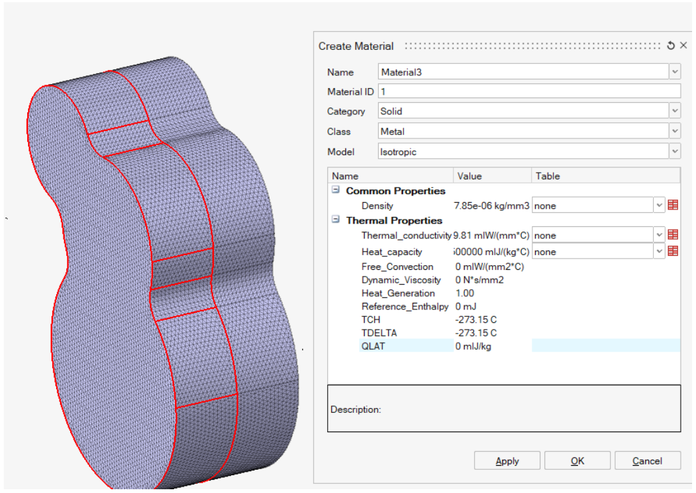
➢ 재료 할당 및 HTC값 mapping

- *유동 해석에서 구한 HTC값을 mapping*

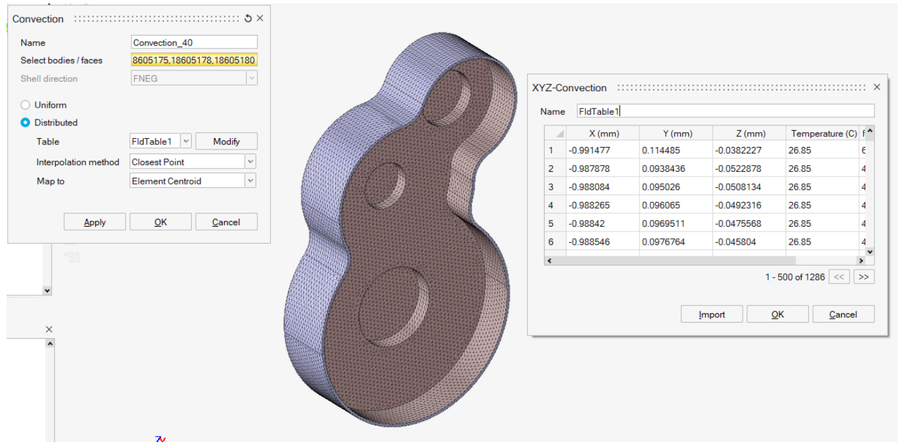
auto contact



material



mapping

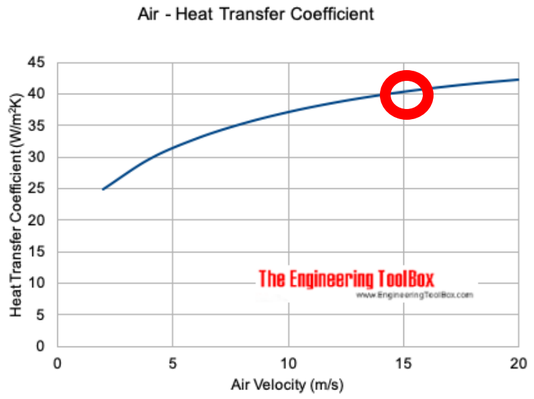


03. 열유체 해석

➢ 경계 조건

- *감속기 외부와 내부의 대류조건*
- *베어링의 heat flux 조건*

Convection



Conditions of heat transfer	W/(m²K)
Gases in free convection	5–37
Water in free convection	100–1200
Oil under free convection	50–350
Gas flow in tubes and between tubes	10–350
Water flowing in tubes	500–1200
Oil flowing in tubes	300–1700
Molten metals flowing in tubes	2000–45000
Water nucleate boiling	2000–45000
Water film boiling	100–300
Film-type condensation of water vapor	4000–17000
Dropsize condensation of water vapor	30000–140000
Condensation of organic liquids	500–2300

베어링 heat flux 구하는 방법

1. 상대속도 계산

$$v = \frac{\pi D_{avg} N}{60}$$

2. 열 발생량 계산

$$Q = \mu P v$$

3. 열 유속 계산

$$q = \frac{Q}{A}$$

4. 단위 변환

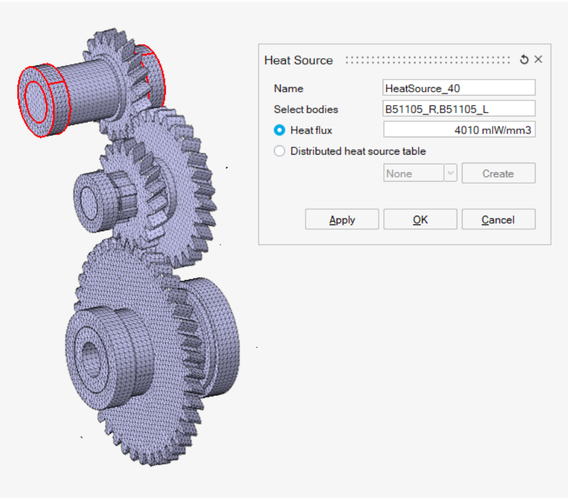
$$W/m^2 \rightarrow mW/m^3$$

$$q_{m\,W/m\,m^3} = \frac{q \times 1000}{A_{m\,m^3}}$$

할당

베어링 위치	Input	Mid	Ouput_L	Output_R
Heat flux	*3153.949*	*6136.575*	*896.1391*	*512.4994*

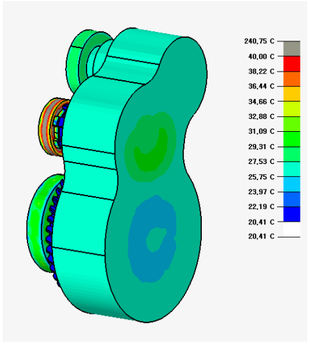
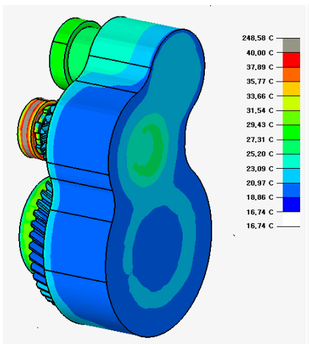
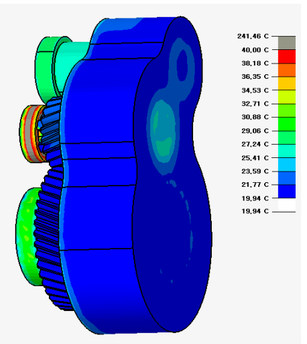
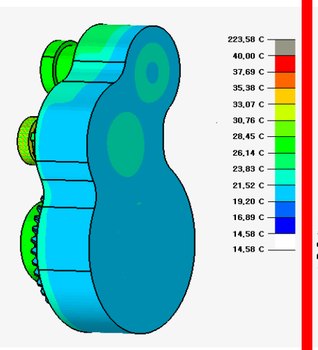
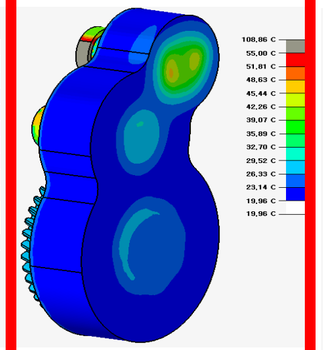
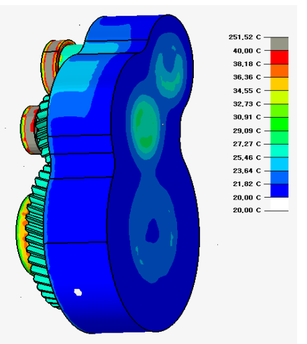
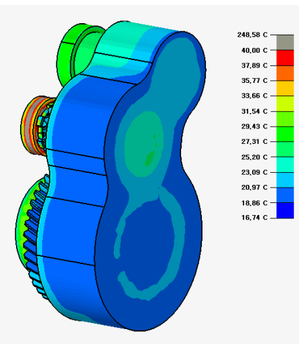
Altair Heat Source 입력

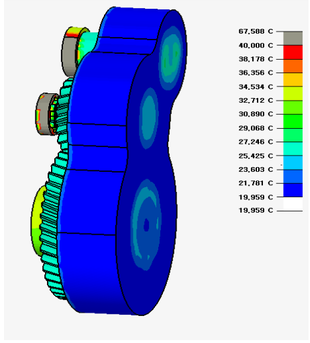
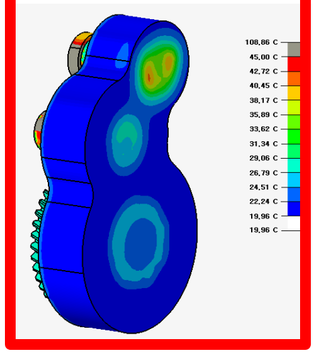
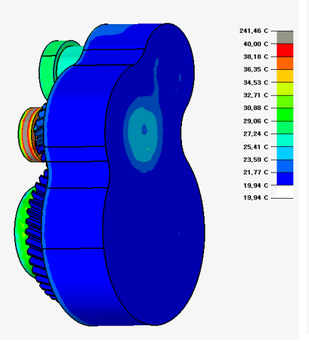
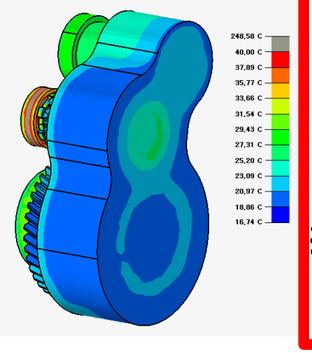
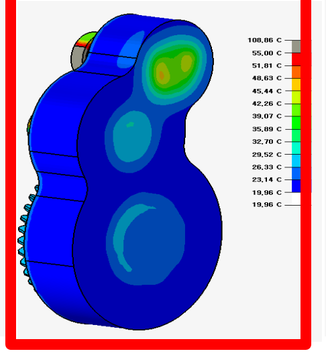
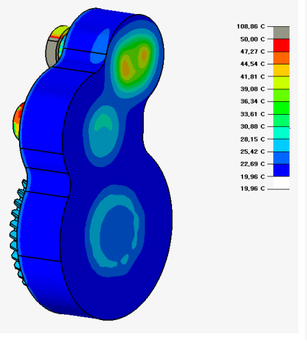
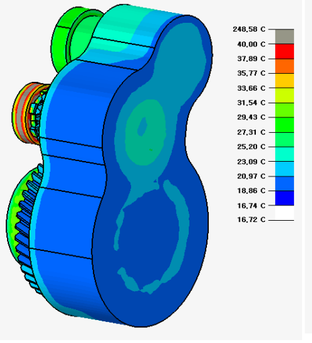
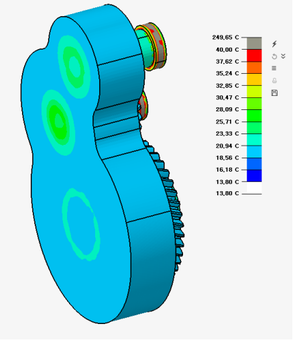


03. 열유체 해석

➢ 해석 결과

- *case 5, 9, 12번은 구속조건 이상의 값으로 해석됨*

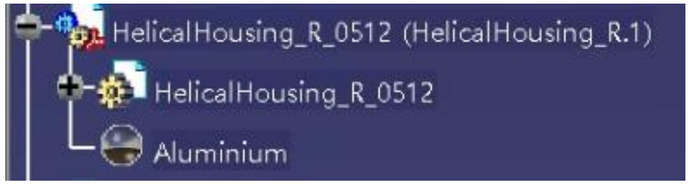
case	1	2	3	4	5	6	7
온도	34.66 °	33.66 °	29.06 °	33.07 °	51.81 °	34.55 °	33.66 °
							

8	9	10	11	12	13	14	15
32.712 °	42.72 °	27.24 °	33.66	48.63	44.54 °	31.54	32.85 °
							

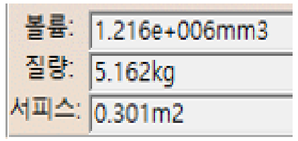
04. 무게 최적화

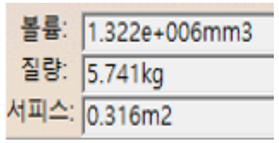
➢ 감속기의 무게

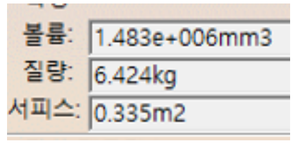
Catia의 material tool을 사용하여 무게 측정

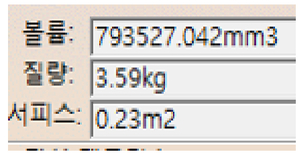


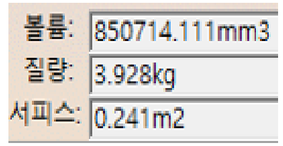
case	1	2	3	4	5	6	7
질량	5.162kg	5.741kg	6.424kg	3.59kg	3.928kg	4.841kg	7.081kg

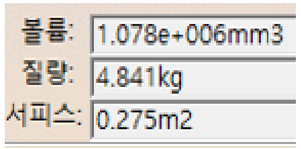


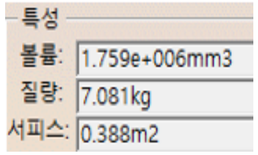




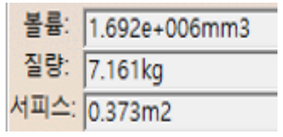


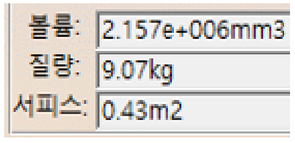


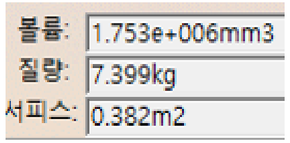


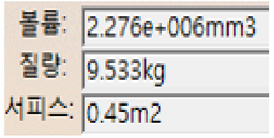


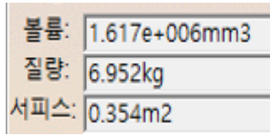
8	9	10	11	12	13	14	15
7.161kg	9.07kg	7.399kg	9.533kg	6.952kg	4.871kg	3.68kg	3.821kg

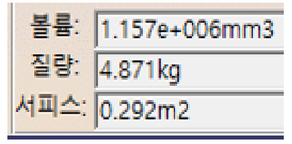


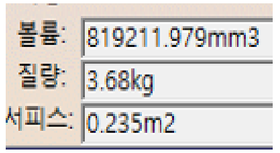


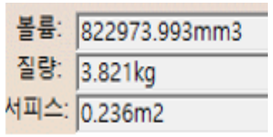








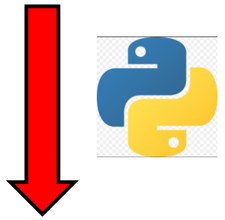




04. 무게 최적화

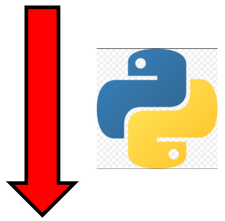
➢ 감속기의 무게

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \beta_{24} x_2 x_4 + \beta_{34} x_3 x_4$$



Python 코드를 사용하여 beta값을 추출

```
beta1
array([ 8.20464359e+01, -4.91922821e+01,  6.33351282e-01,  2.84115385e-01,
       -3.63507906e-01,  8.14430769e+00, -7.05179487e-02, -7.68066667e-02,
        1.60053419e-03,  8.83435897e-02, -4.46687179e-01,  9.58572650e-02,
        1.68621538e-01, -8.17170940e-03, -4.08803419e-04])
```



Scipy 모듈의 minimize ‘SLSQP’를 사용하여 최적화

```
Optimal x values: [ 2.99727897 19.99889286 20.         89.99999835]
```

모듈 이나비 비틀림각 오일level

```
Minimum absolute y value: 10.266865366934562
```

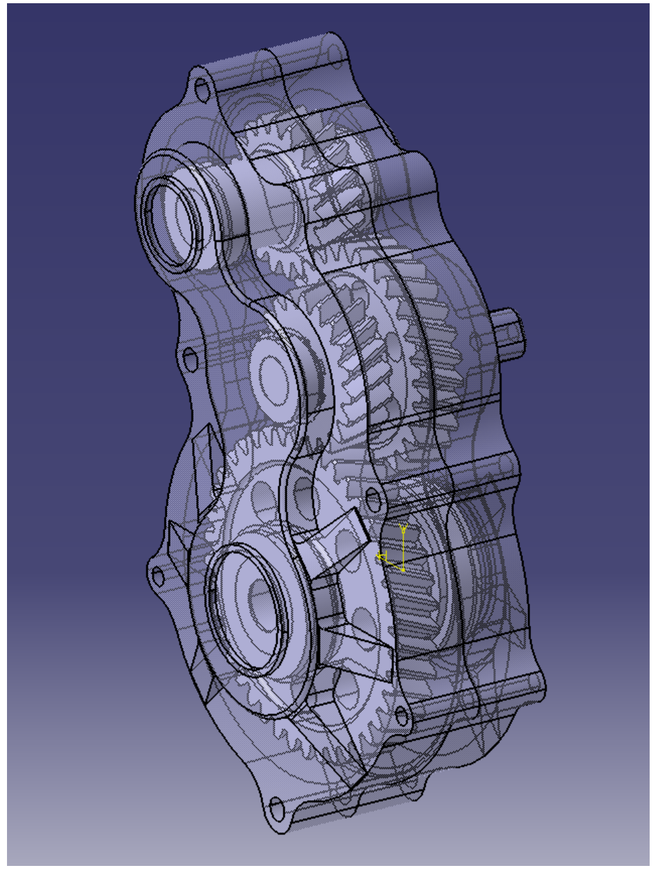
무게

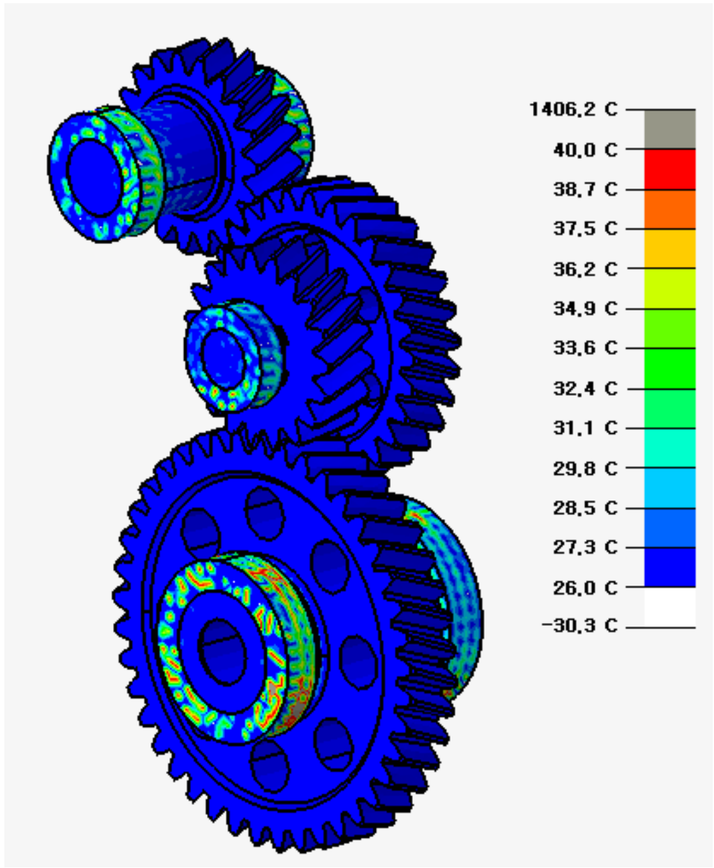
05. 최적값 확인

➢ 강성 및 온도 확인

기어	허용전달동력(kW)
Input	11.285
Mid1	12.3478
Mid2	10.8286
output	11.75395

강성 만족

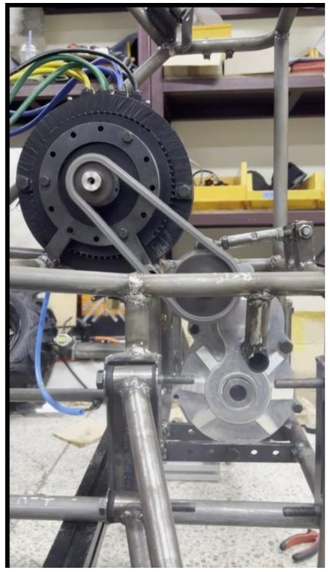




온도 만족

06. 실제 실험

➢ 열화상 카메라로 온도 측정



감사합니다