Effect of Hight Altitude for Electronical Cooling

Flex, Power System
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CONFIDENTIAL

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Agenda

1) Air Properties with Altitude

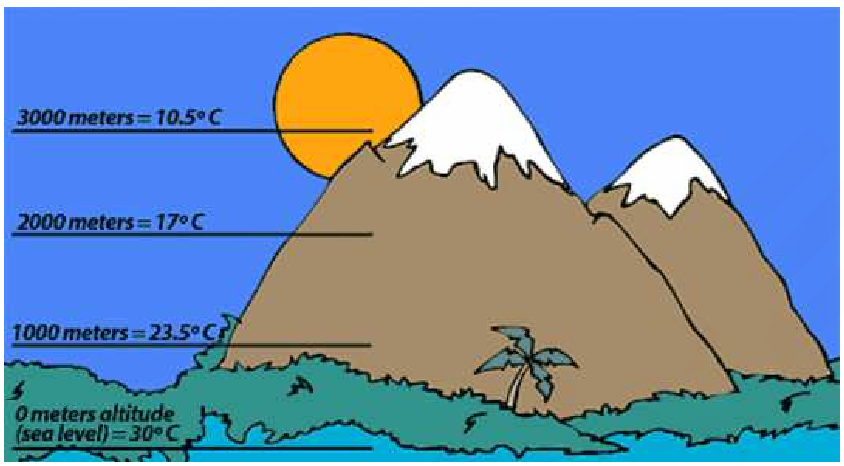
2) Air Density Effects to Cooling Performance

3) Thermal Calculation & Simulation

4) Conclusion

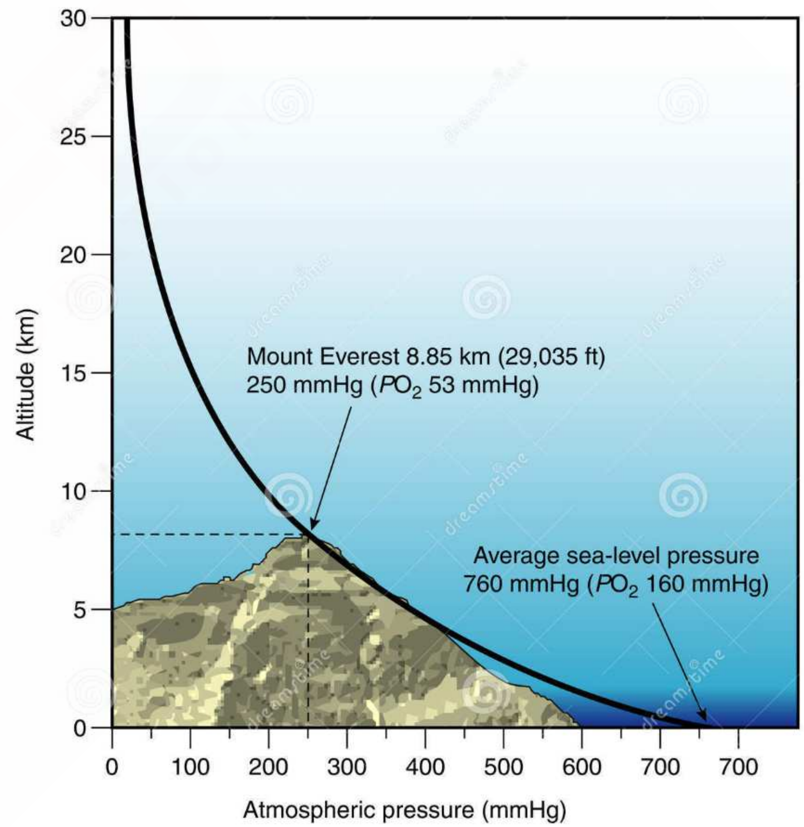
Altitude Affect Pressure & Temperature

Temperature and Altitude



Altitude increase 100 m up, the temperature of air drop 0.65 deg. C

Pressure and Altitude



Altitude vs. Pressure

(Left) At high altitude the air pressure is the same inside and outside the bottle.

(Right) At sea level, the pressure is greater outside than inside the bottle. The greater outside pressure crushes the bottle.

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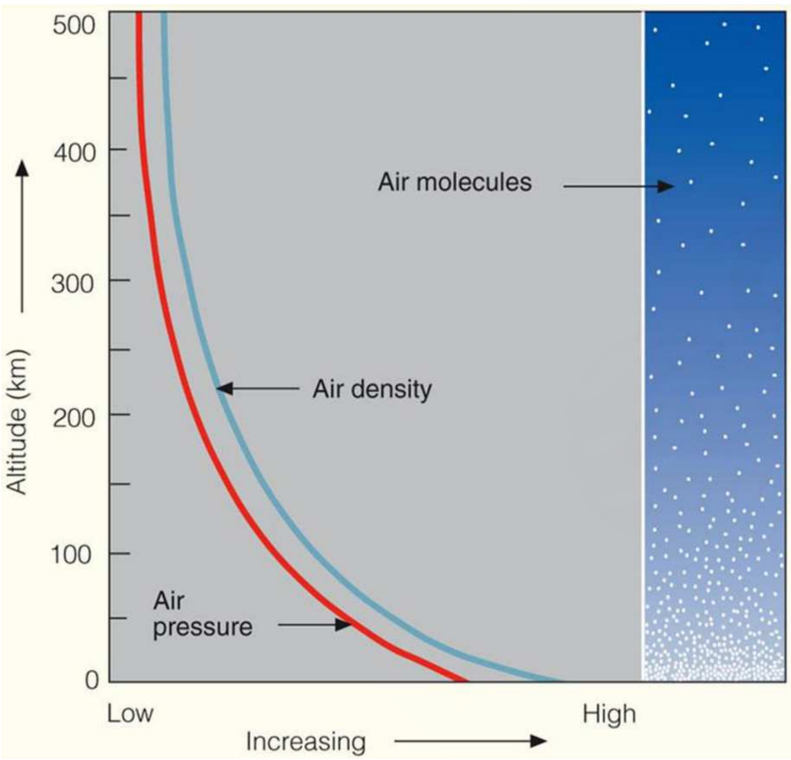
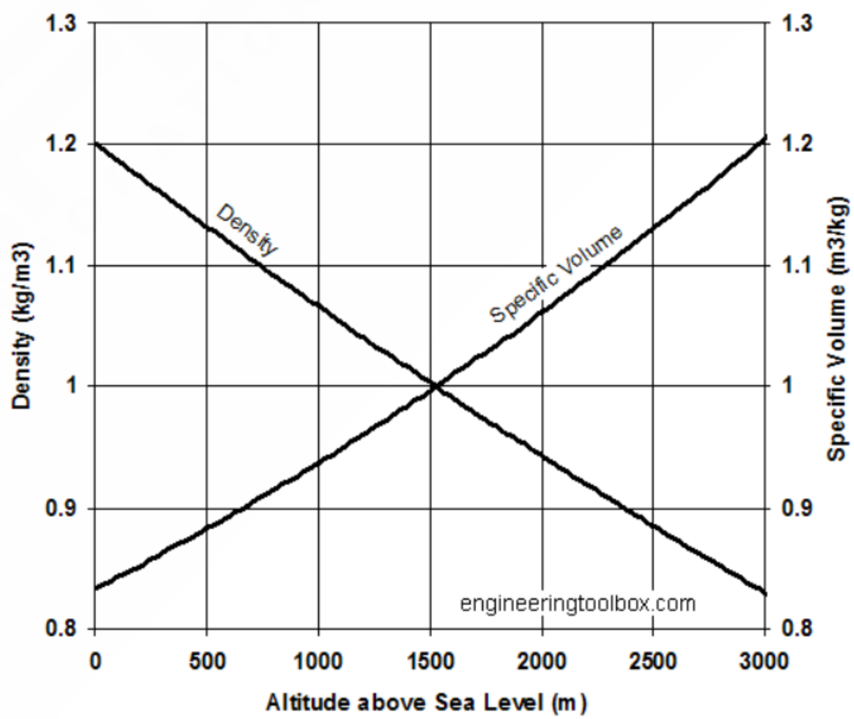
Altitude vs. Air Density

Both air pressure and air density decreases with increasing altitude. It also changes with variances in temperature or humidity. At sea level and at 15 °C according to ISA (International Standard Atmosphere), air has a density of approximately 1.225 kg/m^3 (0.0023769 slugs/ft^3).





Ideal Gas Law

The **Ideal Gas Law** relates pressure, temperature, and volume of an **ideal or perfect gas**.
The Ideal Gas Law can be expressed with the **Individual Gas Constant**:

$$\boxed{P \cdot V = n \cdot R \cdot T} = \left(\frac{W}{M}\right) \cdot R \cdot T$$

$$P \cdot M = \left(\frac{W}{V}\right) \cdot R \cdot T = \boxed{\rho} \cdot R \cdot T$$

where

P = absolute pressure (N/m²)

V = volume (m³)

$n = \left(\frac{W}{M}\right)$ = *amount of substance of gas (moles)*

W = mass of the gas (kg), M = molar mass (kg/mole, Air=28.96 kg/mole)

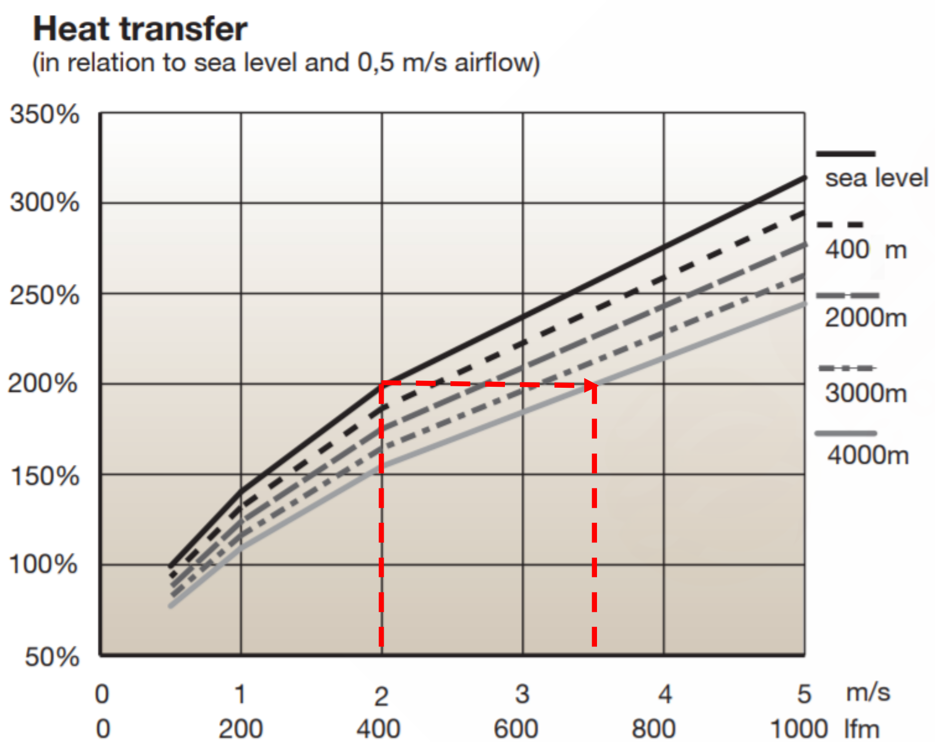
R = individual gas constant (J/mole·K, 8.3143 J/mole·K)

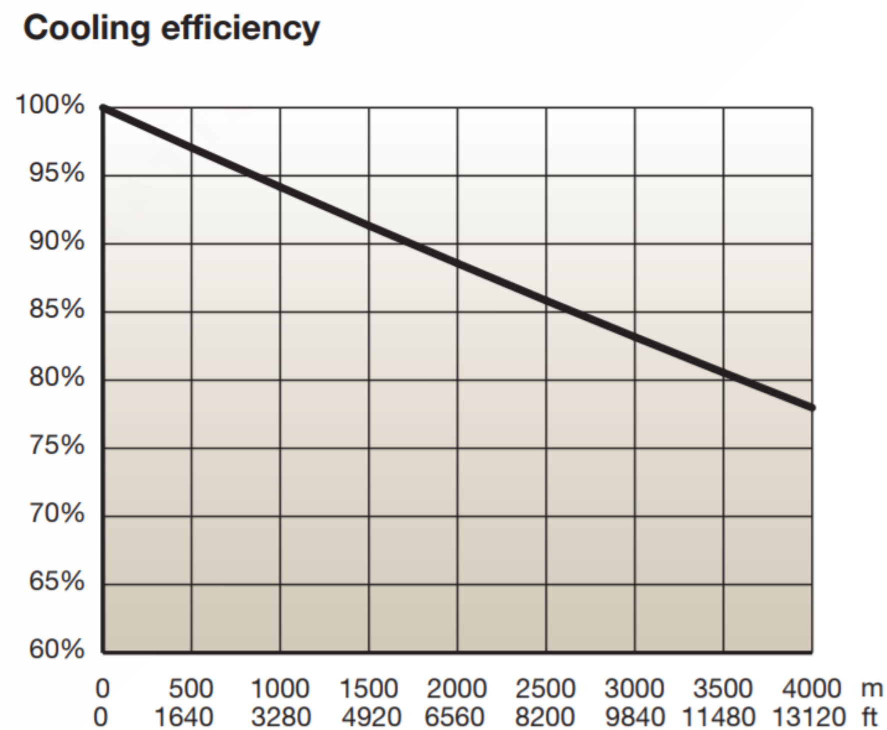
T = absolute temperature (K)

$\rho = \left(\frac{W}{V}\right)$ = *density (kg/m³)*

Heat Transfer Capability at High Altitude

Due to lower air density at higher elevations, the convective heat transfer capabilities of air can vary depending on elevation.





Air Density Effects to Cooling Performance

- Effect 1 - Mass Flow Rate

$$Q = \dot{m} \cdot Cp \cdot \Delta T = \rho \cdot V \cdot Cp \cdot \Delta T$$

Airflow temperature rise (inlet vs. outlet) increased as lower density (less mass flow)

- Effect 2 - Heat Transfer Coefficient

$$Q = h\ A\ \Delta T \ \rightarrow Nu = \frac{h \cdot L}{k}$$

Heat transfer coefficient is changed with air density ratio.

$$Nu = f(Re \cdot Pr) \rightarrow Forced\ Convection$$
$$Nu = f(Gr \cdot Pr) \rightarrow Natural\ Convection$$

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Effect 1 : Mass Flow Rate

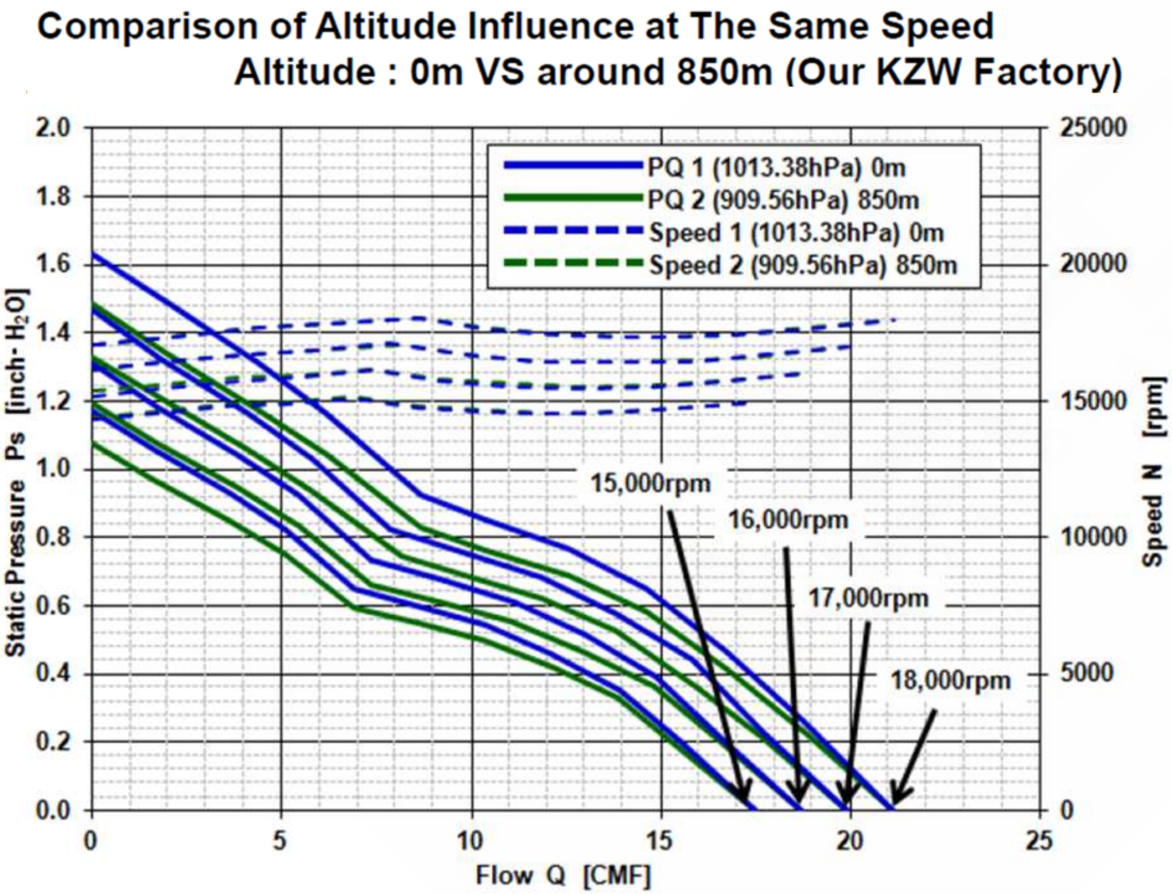
In forced-air-cooled systems, the heat transfer can also be expressed as

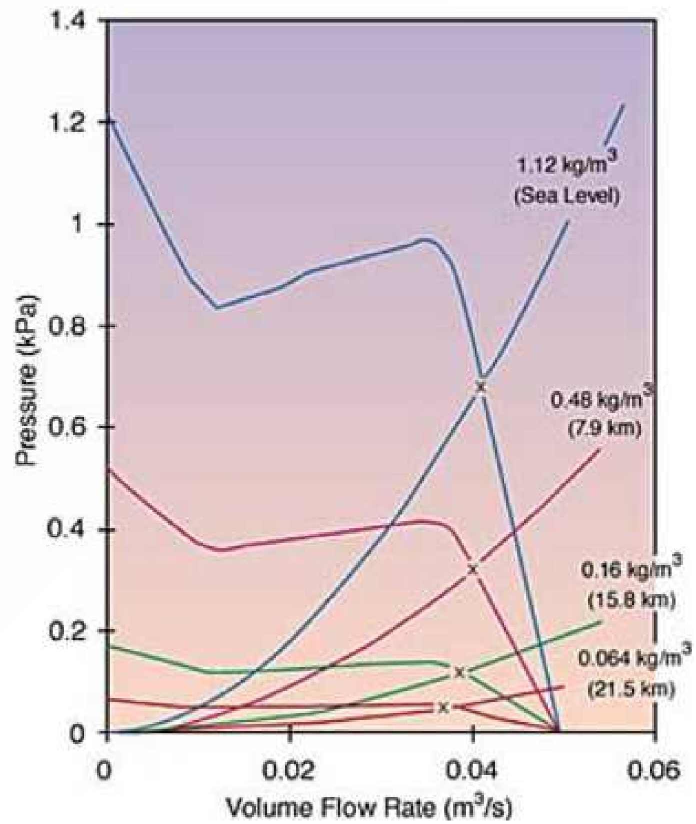
$$\dot{Q} = Constant = \underset{\downarrow}{\dot{m}} \cdot Cp \cdot \underset{\uparrow}{\Delta T} = \underset{\downarrow}{\rho} \cdot V \cdot Cp \cdot \underset{\uparrow}{\Delta T}$$

A fan at a fixed speed (or fixed rpm) will deliver a <u>fixed volume of air</u> regardless of the altitude and pressure. However, the mass flow rate of air will be decrease at high altitude as a result of the lower density of air.

The temperature effect – the delta T increases by the ratio of densities as the altitude is increased.

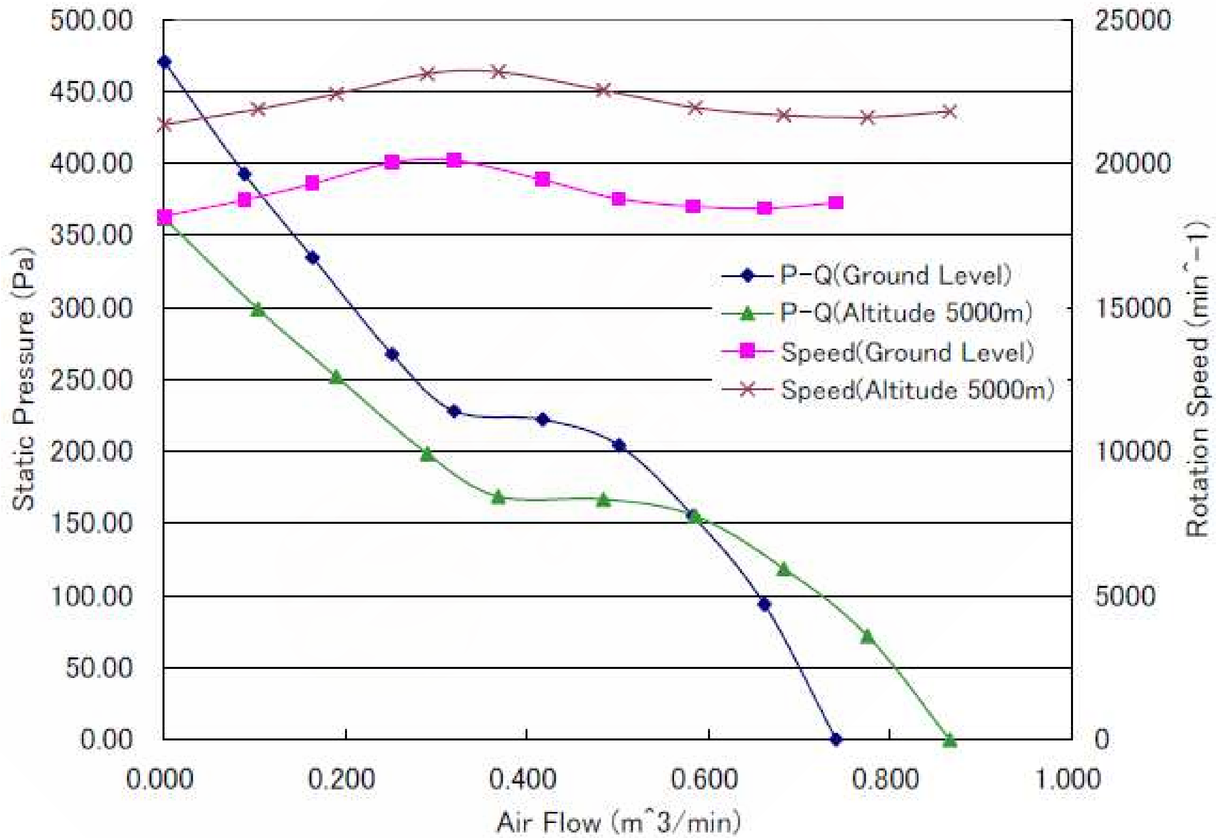
Fan PQ Behavior at High Altitude – Same Speed





NMB Fan 4028 1611FB-E4W-B86-B53 18000 rpm

Fan PQ Behavior at High Altitude – Same Power



Nidec Fan 4028 W40S12BS4A5 18000 rpm

Effect 2 : Heat Transfer Coefficient

- Forced Convection

The average Nusselt number is generally a function of Reynolds number and Prandtl number

$$\mathrm{Nu} = \frac{\mathrm{h}L}{\mathrm{k}} = \mathrm{C}\,\mathrm{Re}^{\mathrm{m}}\,\mathrm{Pr}^{\mathrm{n}}$$, $n = 0.33$, refer to Empirical Correlation

$$\mathrm{Re} = \frac{\rho u L}{\mu} = \frac{uL}{\nu}$$

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\text{viscous diffusion rate}}{\text{thermal diffusion rate}} = \frac{\mu/\rho}{k/(c_p\rho)} = \frac{c_p\mu}{k}$$

- Natural Convection

The average Nusselt number is expressed as a function of Grashof number and Prandtl number

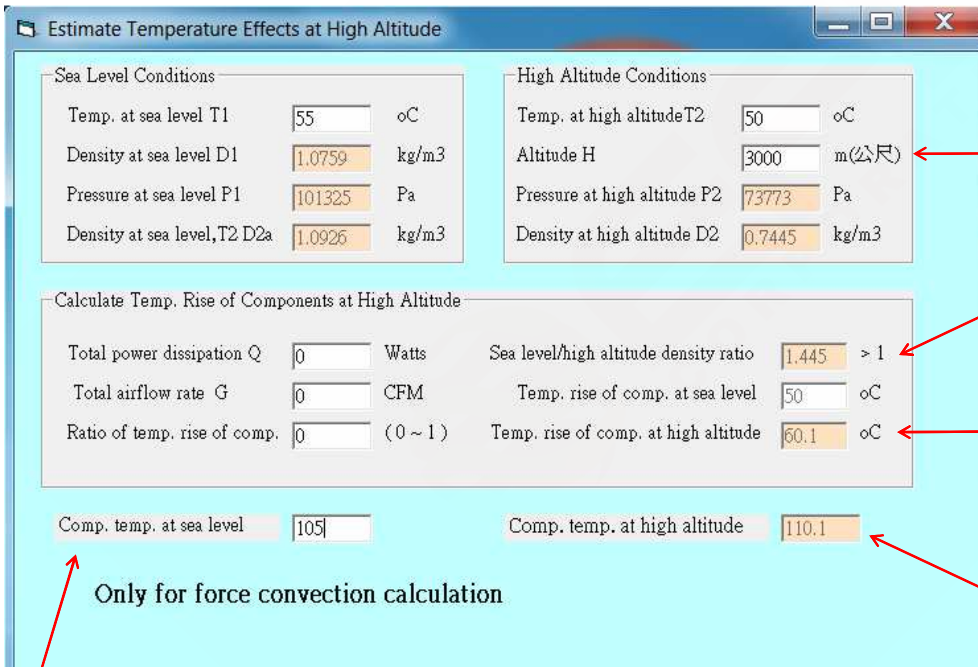
$$\mathrm{Nu} = \frac{hL}{k} = C\,(\mathrm{Gr}\cdot\mathrm{Pr})^{1/4}$$, refer to Empirical Correlations

$$\mathrm{Gr}_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$$

$$\nu = \frac{\mu}{\rho}$$

Estimate Component Temp. at High Altitude

For components temperature is 105 deg. C at ambient 55 deg. C, estimate the temperature at 3000m and 50 deg. c ambient.



Input altitude high (m)

Density ratio ($\frac{\rho_1}{\rho_2}$)

Component Temp. Rise (at high altitude)=

Temp. rise (at sea) * Density ratio ($\frac{\rho_1}{\rho_2}$) $^{1/2}$

Component Temp. (at high altitude)= Temp. rise (at high altitude) + ambient at high altitude

Input components temperature at sea level

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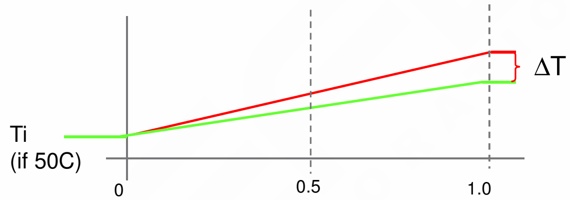
Consider Ambient Temp. Rise

Considering the temp. rise (out and inlet) of airflow will increased at high altitude due to lower density at high altitude.

Airflow In → T_{in}, $\dot{m}$

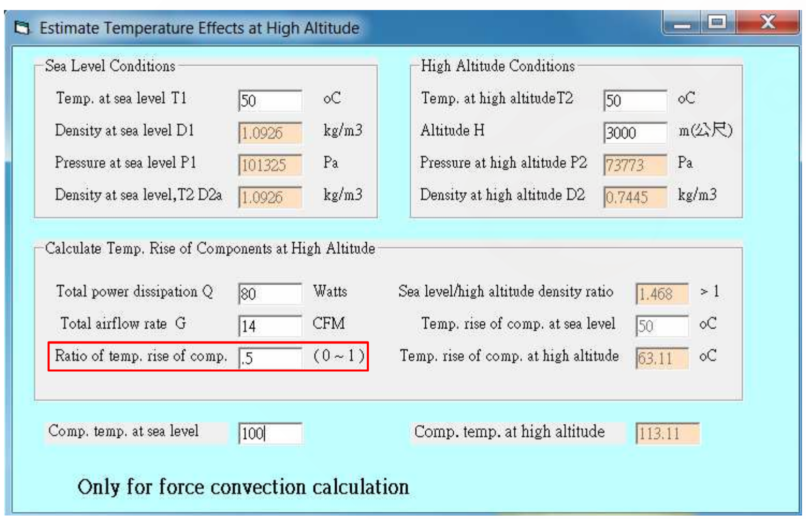
$$\Delta T = \frac{Q}{\dot{m} \cdot Cp}$$

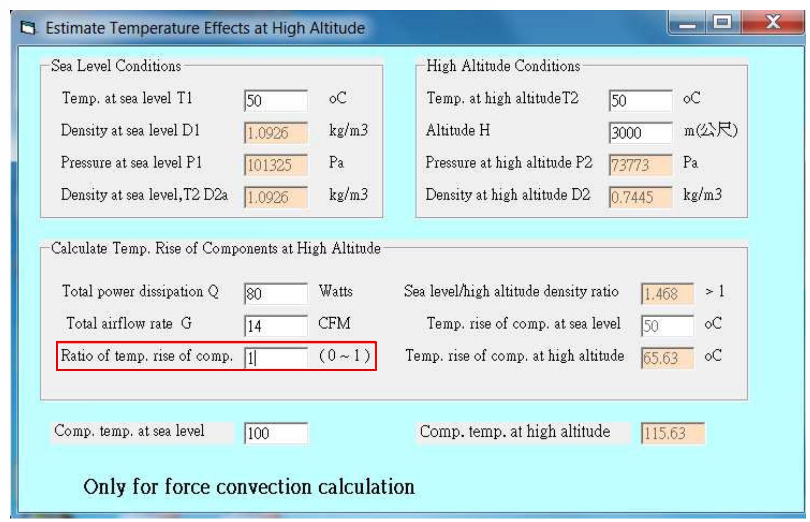
→ T_{out}, $\dot{m}$ → Airflow Out



$T_{L=1.0}$ = 65.6 C (or 15.6C rise)

$T_{L=0.5}$ = 63.1 C (or 13.1 C rise)





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Altitude Correlation Coefficient

Temp (altitude) = [Temp (sea-level) – ambient] x correlation coefficient + ambient

- *Customer "Cxxxx"*
  1800m or 6,000ft = 1.15
  3000m or 10,000ft = 1.24

- *Customer "Sxxxxxx"*
  2000m = 1.16
  3048m = 1.26
  4000m = 1.35

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Flotherm – High Altitude Setting

In order to estimate performance of Fan P-Q Curve and Flow Resistance at high altitude condition, Mentor provide a website for user to apply it easier.

Flotherm
http://webparts.mentor.com/flotherm/support/webparts.jsp

or Google the keyword "Flotherm Support Webparts"

Support/Web Parts

1. V6.1 Angled Fan Macro
2. V6.1 Blower Macro
3. Spinning Disc Macro
4. Angled Thick Resistance Macro
5. Thermoelectric Cooler Generator
6. Heated Tube Macro
7. Power Cylinder Macro
8. High Altitude Settings Calculator
9. Manifold Air Duct Generator
10. Chassis Air Guide Generator
11. Advanced Resistance Generator
12. Angled Resistance Generator
13. Tube Generator
14. Elliptic Rod Generator
15. Finned Box Generator

Flotherm – High Altitude Setting

Natural Convection

Besides air density, air expansivity value comes into consideration for buoyancy effects.

Input Data		
Altitude h	(m)	3048
Air Temperature at Altitude T1	(C)	35
Output Data		
Air Density at Altitude ra (atmospheric conditions)	(kg/m3)	0.906965
Expansivity at Altitude ba (atmospheric conditions)	(1/K)	0.003726
Air Temperature at Altitude Ta (atmospheric conditions)	(C)	-4.74152
Air Density at Altitude r2 (user set temperature)	(kg/m3)	0.817032
Expansivity at Altitude b2 (user set temperature)	(1/K)	0.003245
Calculate!	Reset Form	

Ideal Gas Law

$$\rho = \frac{P}{rT}$$

$P(Pa)$: pressure at altitude z.

$r(N.m/kg.K)$: gas constant (ie r = 287 for air).
$T(K)$: expected air average temperature.

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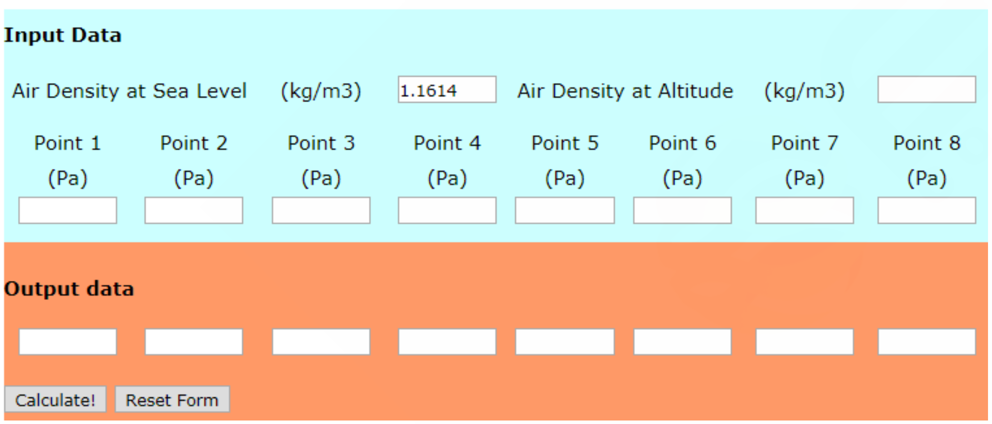
Flotherm – High Altitude Setting

Forced Convection

If there are fans in the system, fan curve need to have its pressure curve being modified to take the density variation into account. (assume fan is a constant speed air moving device)

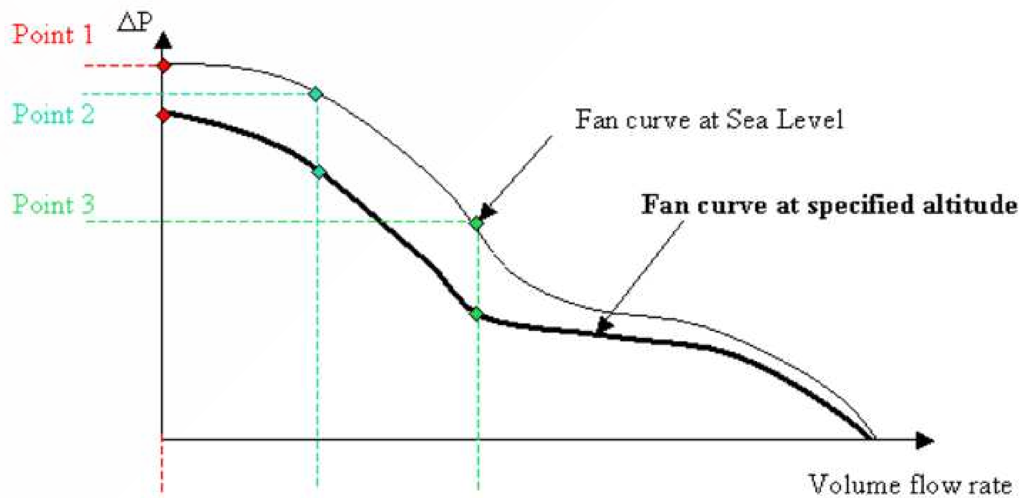

Input Data

Air Density at Sea Level (kg/m3) 1.1614 Air Density at Altitude (kg/m3)

Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8
(Pa)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)

Output data

Calculate! Reset Form



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Flotherm – High Altitude Setting

Planar and Volume Flow Resistances

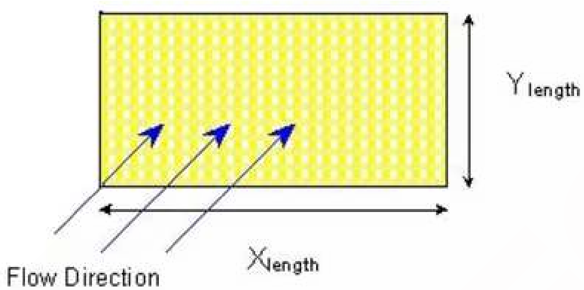


Figure1. Planar Resistance

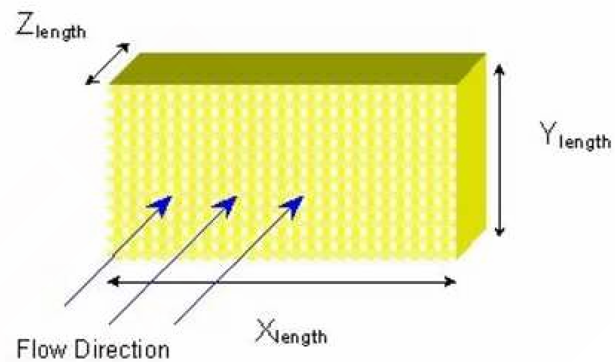
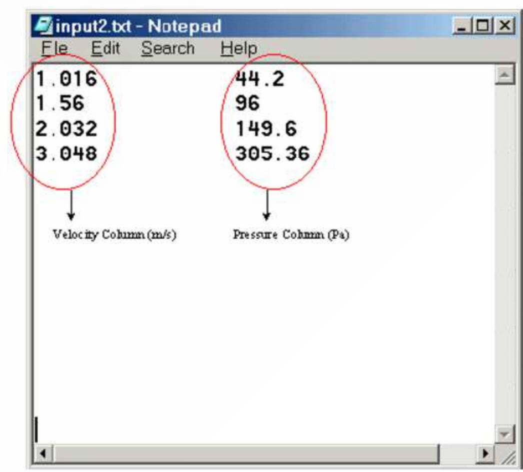


Figure 2. Volume Resistance

Enter the total number of data points, N **(To obtain an accurate model of a resistance, please make sure that you have a minimum of 3 data points)**	5	
Density of fluid (default value is for air at 300 K)	1.1614	kg/m^3
Viscosity of fluid (default value is for air at 300 K)	1.84e-05	$N\text{-}s/m^2$
X_{length}(width)	.2	m
Y_{length}(height)	.1	m
Z_{length}**(*1)**(thickness)	.008	m

$$\mathrm{Re} = \frac{\rho u L}{\mu}$$



Generate PDML

Import to Project

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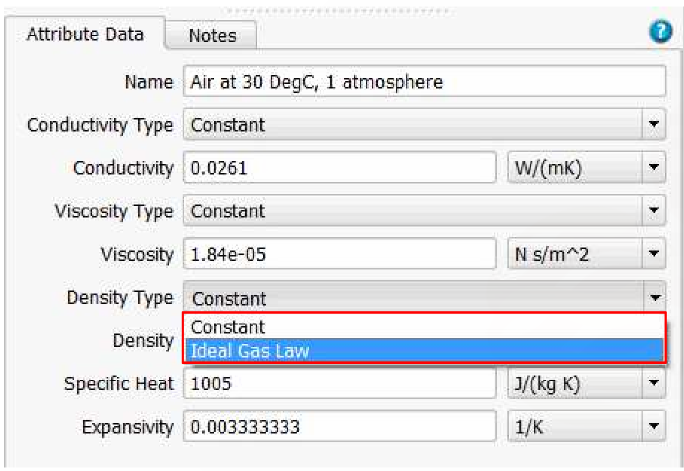
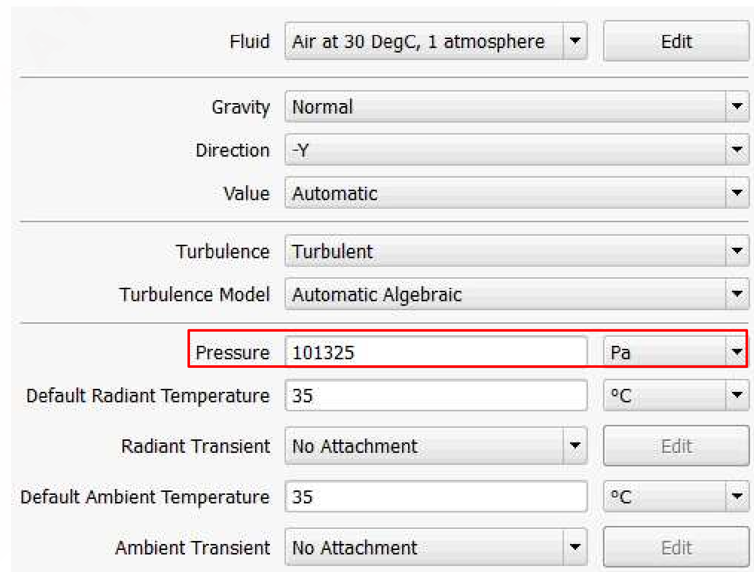
Flotherm – High Altitude Setting

- Density can be set as being constant throughout the computational domain. Density is assumed to be constant if the variation in the fluid temperature is less than 60˚C in the domain.
- Density can vary using the Ideal Gas Law when the density variations due to temperature or molecular weight are significant (more than 60˚C).





Comparison with Estimation and Simulation

Example

Unit operating at sea-level & 55C is known and estimate thermal performance at 3048m & 55C.

Condition #1			Condition #2		
Altitude, H_1	0	m	Altitude, H_2	3048	m
Temp. T_1	55	degC	Temp. T_2	55	degC
Pressure, P_1	101325	Pa	Pressure, P_2	69681.7	Pa
Density, ρ_1	1.076	kg/m^3	Density, ρ_2	0.740	kg/m^3
Kinematic Viscosity, υ_1	1.8372E-05	m^2/s	Kinematic Viscosity, υ_2	2.6715E-05	m^2/s
Dynamic Viscosity, μ_1	1.9763E-05	kg/m s	Dynamic Viscosity, μ_2	1.9763E-05	kg/m s
Specific Heat, Cp_1	1006.99	J/kg C	Specific Heat, Cp_2	1006.99	J/kg C
Thermal Conductivity, k_1	0.0283	W/m K	Thermal Conductivity, k_2	0.0283	W/m K
Thermal Diffusivity, α_1	2.6156E-05	m^2/s	Thermal Diffusivity, α_2	3.8034E-05	m^2/s
Prandtl Number, Pr_1	0.702		Prandtl Number, Pr_2	0.702	

- Altitude correlation coefficient

$$Nu = \frac{hL}{k} = C\,Re^m\,Pr^n$$

$$Re = \frac{\rho u L}{\mu} = \frac{uL}{\nu}$$

- Temp(altitude) = Temp Rise(sea-level) x correlation coefficient + ambient(altitude)

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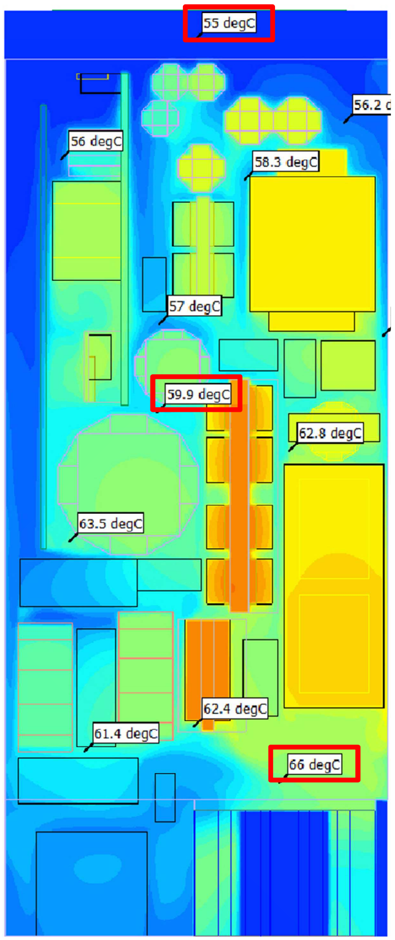
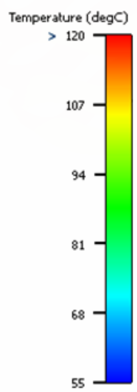
Example - Simulation Comparison (Surrounding Temp.)

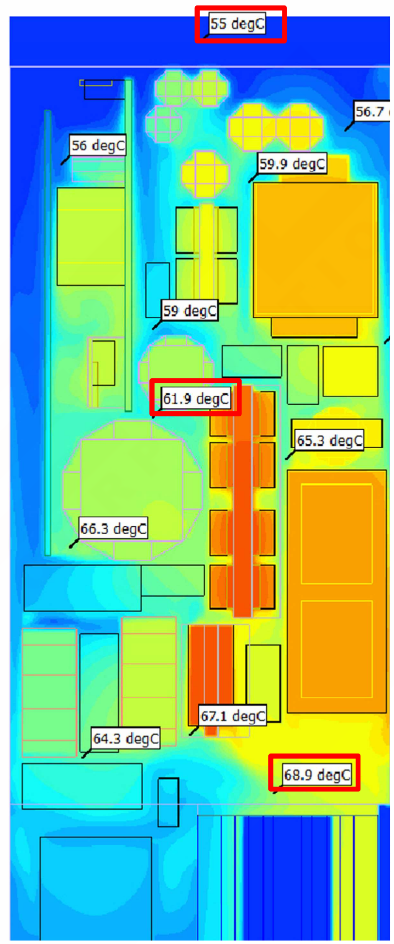
Airflow Direction

Sea Level





3000m



Component	Sea-Level	3000m	Deviation
Inlet	55.0	55.0	0.0
Up-T1	57.2	58.5	1.3
Up-HS3	55.3	55.5	0.2
Up-Boost Cap	55.6	56.0	0.4
Up-HS2	57.2	58.3	1.1
Up-Nearby HS2	60.5	63.1	2.6
Up-L4	61.3	64.1	2.8
Up-CM Choke	60.1	62.4	2.2
UP-Neaby BD1	62.6	66.3	3.7
Outlet Mean Temp.	63.3	67.0	3.7
Aiflow Rate (CFM)	11.64	11.64	0.0

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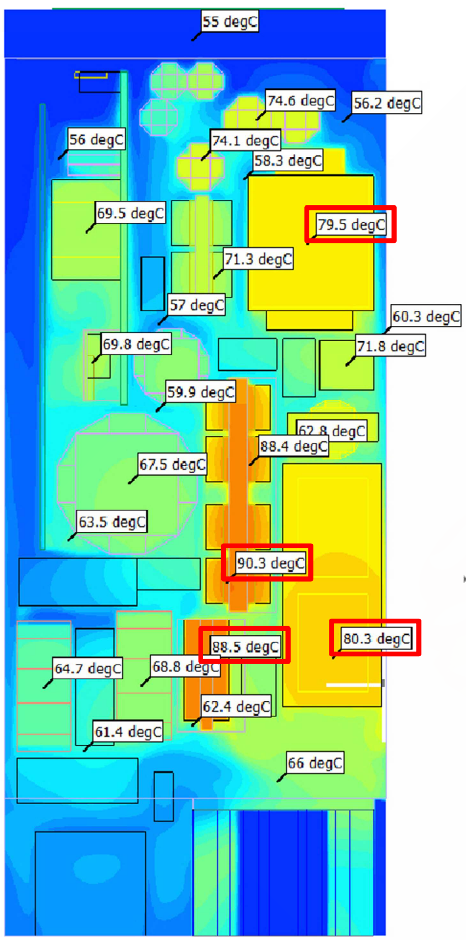
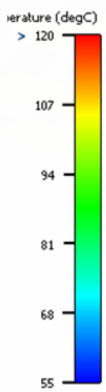
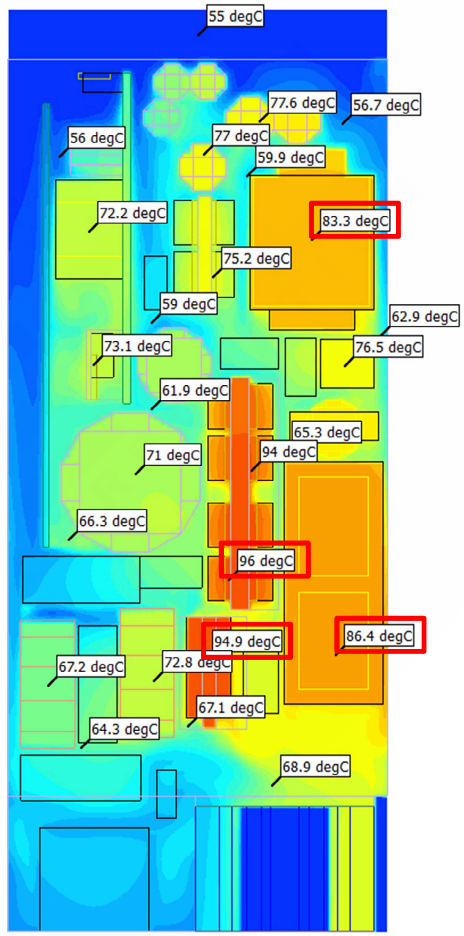
Example - Simulation Comparison (Component Temp.)

Sea Level





3000m



Airflow Direction

Component	Sea-Level	3000m	Deviation
BD1	89.0	95.5	6.5
Q1	87.7	93.4	5.7
Q4	87.1	92.7	5.6
D3	88.5	94.2	5.7
D4	87.8	93.4	5.6
D6	86.8	92.3	5.5
Q12	82.3	87.6	5.2
Q9	85.3	90.6	5.3
Q7	83.9	89.4	5.4
Q127	70.7	73.6	3.0
L3-2	79.8	85.8	6.0
L3-1	80.3	86.4	6.1
T1	79.6	83.3	3.7
L4	74.0	78.9	4.8
T300	69.5	72.2	2.7
Q302	69.4	72.7	3.3
L1	64.4	66.9	2.5
L2	68.6	72.5	3.9
C3	66.7	70.1	3.4
C9	66.7	69.2	2.6
RL1	57.9	59.6	1.7
Q102	71.8	74.6	2.7

Comparison with Estimation and Simulation

Componen	Simulation	Estimation	Deviation		Componen	Simulation	Estimation	Deviation	
$T_{out\ Mean}$	67.0	65.4	-1.61	2.4%	L3	88.0	86.7	-1.36	1.5%
BD1	95.9	97.6	1.64	1.7%	T1	84.1	85.8	1.72	2.0%
BD2	95.9	97.5	1.66	1.7%	L4	79.8	78.8	-0.94	1.2%
Q1	94.5	96.0	1.46	1.5%	T300	72.7	73.1	0.39	0.5%
Q4	93.9	95.2	1.35	1.4%	Q303	72.2	72.7	0.47	0.7%
D3	95.4	96.9	1.53	1.6%	Q302	73.5	73.1	-0.44	0.6%
D4	94.6	96.1	1.47	1.6%	D311	70.2	71.9	1.64	2.3%
D6	93.4	94.9	1.42	1.5%	L1	67.3	66.8	-0.47	0.7%
Q12	88.7	89.2	0.51	0.6%	L2	73.0	72.0	-0.98	1.3%
Q9	91.6	92.9	1.32	1.4%	C3	70.5	69.7	-0.83	1.2%
Q7	90.5	91.2	0.72	0.8%	C9	69.5	69.6	0.12	0.2%
Q127	74.1	74.6	0.49	0.7%	CT1	78.0	76.6	-1.41	1.8%
Q129	74.8	75.8	0.92	1.2%	Q102	75.1	76.0	0.91	1.2%
Q120	73.4	74.0	0.58	0.8%	Q101	75.3	76.3	0.96	1.3%
Q128	75.0	75.9	0.90	1.2%	Q119	75.0	76.0	0.96	1.3%

Compare with simulation data, It’s around 1~2.5 % difference by experience correlation.

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Summary

- Understand air properties variation at high altitude. (temperature, pressure, density…)
- At urgent case, it's easy to get an approximate result by a quick/simple heat transfer equation.
- While setting high altitude simulation by Flotherm, don't forget to adjust those key properties that may vary by altitude.

Thank You