A Method for Approximating Component Temperatures at Altitude Conditions Based on CFD Analysis at Sea Level Conditions

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Introduction

In many electronics applications, there is a need to understand the performance of a system at different altitude conditions. It is also common in a development cycle, to perform extensive analysis and validations at sea level conditions, and then have to extrapolate these results to altitude conditions. A simple method that could be used to obtain good approximation of the component temperatures without having to re-run the CFD analysis at various altitude conditions would be a very valuable tool for the thermal design engineer.

In this paper, we discuss a method that has worked well for us in a number of cases.

The objective is to perform a CFD analysis of the electronics system at sea level, and on this basis, make an assessment of the system at altitude conditions without re-running a full-blown CFD analysis. The methodology described below reviews the assumptions made in developing the technique as well as a comparison against actual CFD results at altitude conditions.

Methodology

The methodology discussed is applied to an indoor telecommunication rack. In order to establish that the technique works well, we will run CFD analyses of the system at sea level and then altitude conditions to establish baseline data. We will then apply the correlation to the system and provide a comparison against the CFD baseline data.

Fluid properties, pressure drop, and fan curves

We will first review the assumptions that we make as regards the air properties and other parameters required for the CFD analysis.

Based on air property data, we make the assumption that viscosity, conductivity, and specific heat of air are only secondary order parameters. The air density will see the greatest change as the altitude is increased. Therefore, the fluid properties of the model are kept constant in all instances except for the air density, which is modified in accordance with the altitude condition under investigation.

In many cases, pressure drop test data for items such as air filters is only carried out at sea level. We must therefore have some basis for modifying the model parameters to ensure that the flow resistance parameters correspond to the altitude conditions. The pressure drop of a system at altitude can be assumed to change as a function of the density ratio. From this, we can establish new parameters (at altitude conditions) for flow resistances used in our model (Figure 1).

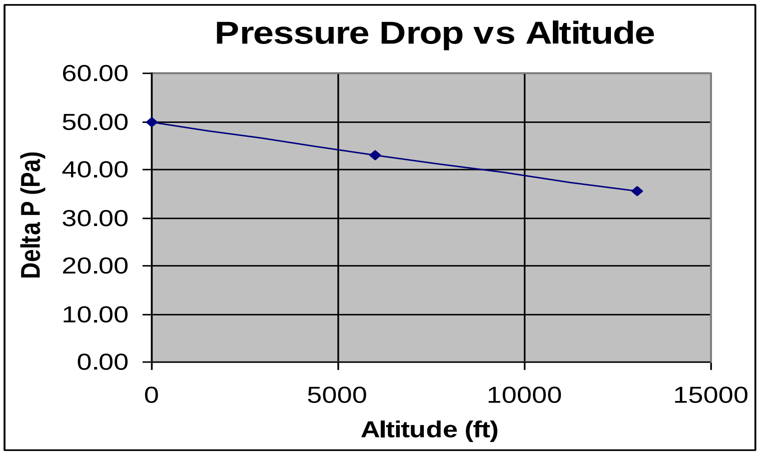


Figure 1

Fan curves are generally available at sea level conditions. We must therefore have some basis for modifying the fan curves to correspond to altitude conditions. For conventional fans, we assume that the fan characteristics change as follows: the volumetric flow at any point on the characteristic curve will remain the same for sea level or altitude; the pressure drop at any corresponding flow rate on the curve will change as the ratio of densities. We can therefore estimate a new fan curve at altitude based on existing sea level data for the same fan (Figure 2).

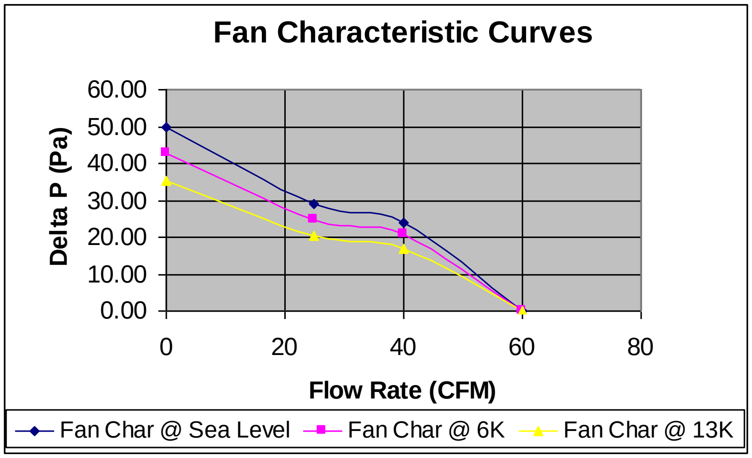


Figure 2

The assumptions above are discussed in some detail in references 1 and 2. It is recommended that the reader review these to obtain a better understanding of the assumptions used here.

System level analysis

The system model is shown schematically in Figure 3. It is a telecommunication rack made up of a number of shelves stacked vertically above each other. A cooling system below the unit delivers air to the full stack of shelves. All shelves are identical and the cards in the shelf are all located in a similar fashion with respect to each other.

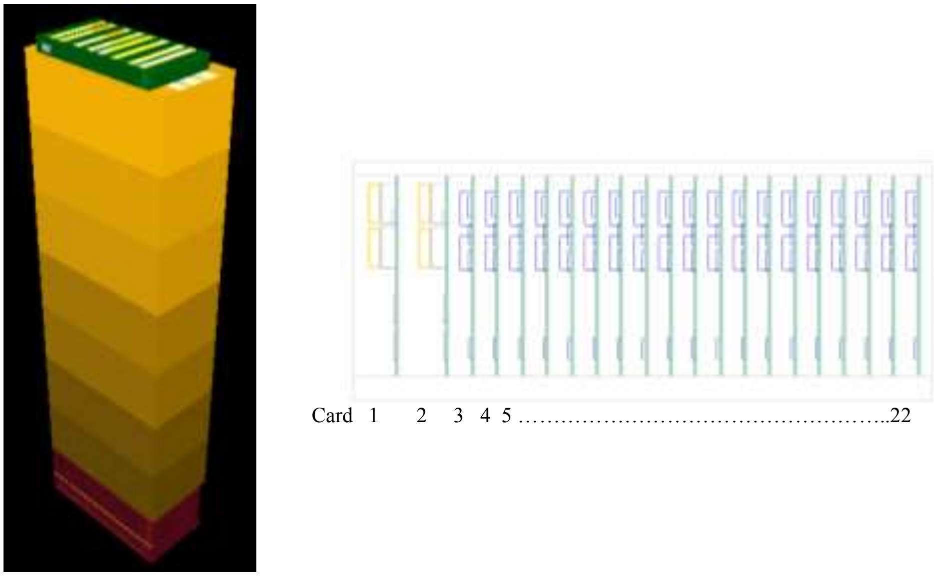


Figure 3

The system level analysis was run at sea level using the CFD software FLOTHERM. The model was then run at altitude (13,000 ft) by modifying certain parameters in the model as discussed previously. Specifically, we ran the model at altitude by changing the fluid properties, fan characteristics, and flow resistance parameters (air filter) to correspond to the new altitude conditions. Subsequent to these runs, we compared the overall system flow rate and delta T as well as the channel flow rates and delta T's.

Zoom-in analysis

Based on the system level analysis, we performed zoom-in analyses of the cards at sea level and altitude conditions; see Figure 4. Again, the zoom-in models at altitude incorporated changes to the fluid properties and flow resistances corresponding to the altitude in question.

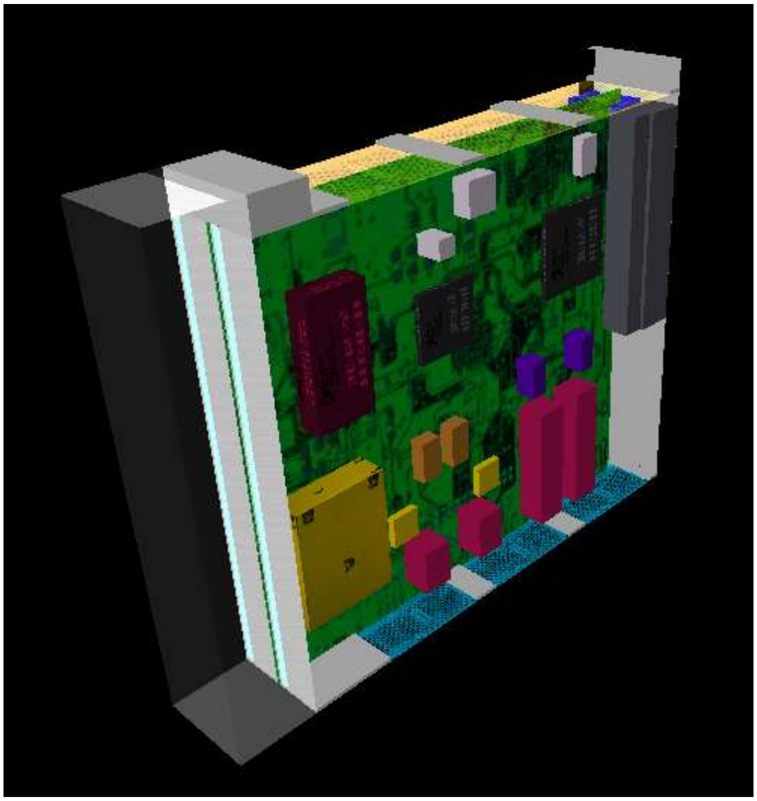


Figure 4

Analysis and results

The analysis was performed on a forced convection system at sea level and 13000 ft altitude.

As discussed above, we ran system level analyses at the different altitude conditions. This allowed us to compare simulation data for the complete system and for the various channels between two cards in a shelf. We subsequently performed zoom-in analyses at the different altitudes, and this allowed us to investigate the changes at the board and component levels.

For the system level analysis, it was found that the operating point of the system had shifted down on the impedance curve as shown in Figure 5.

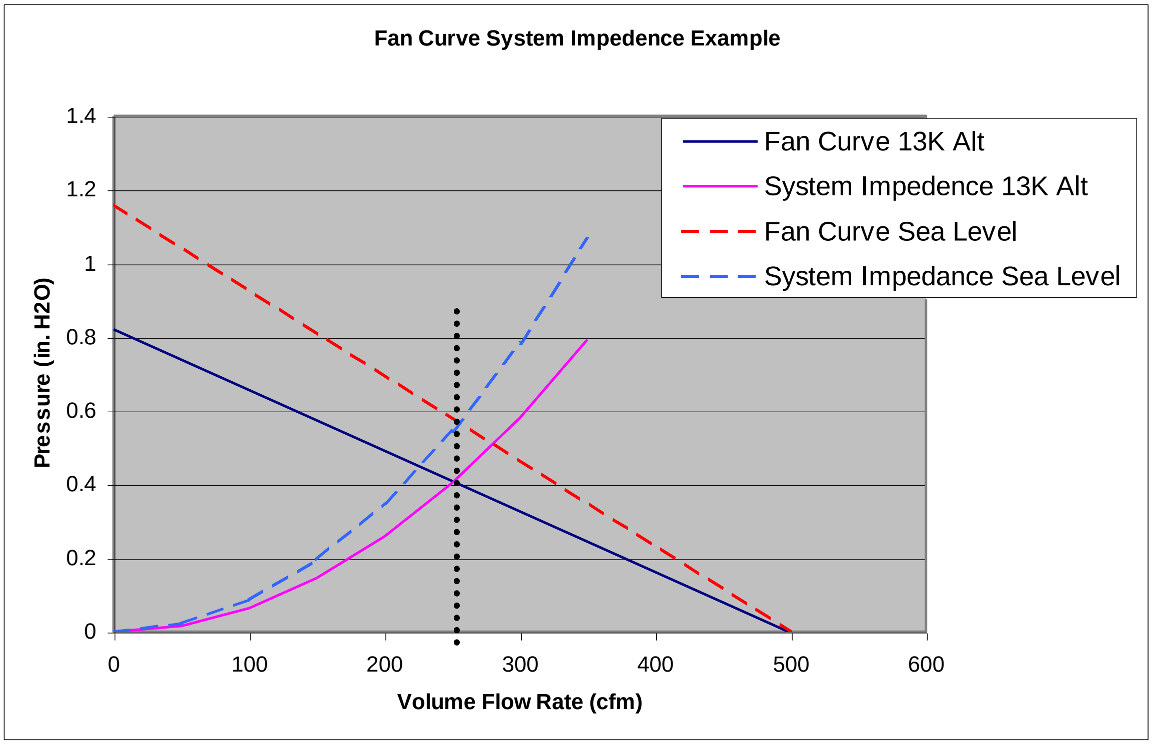


Figure 5

Effectively the system delivers approximately the same flow at the different altitude conditions. Due to the lower fluid density at altitude, this of course means that the mass flow is reduced at these altitudes. The temperature effect of this is that the delta T for the system and also for the individual channels increases by the ratio of densities as the altitude is increased. This can be seen if we consider the following:

$$Q = \dot{m} \cdot C_p \cdot \Delta T = (\rho \cdot V \cdot A) \cdot C_p \cdot \Delta T = \text{Constant}$$

Based on the result that the flow is constant, then Flow rate = V · A = Constant

$$\Delta T = \frac{Q}{(\rho \cdot V \cdot A) \cdot C_p} \quad \alpha \quad \frac{1}{\rho}$$

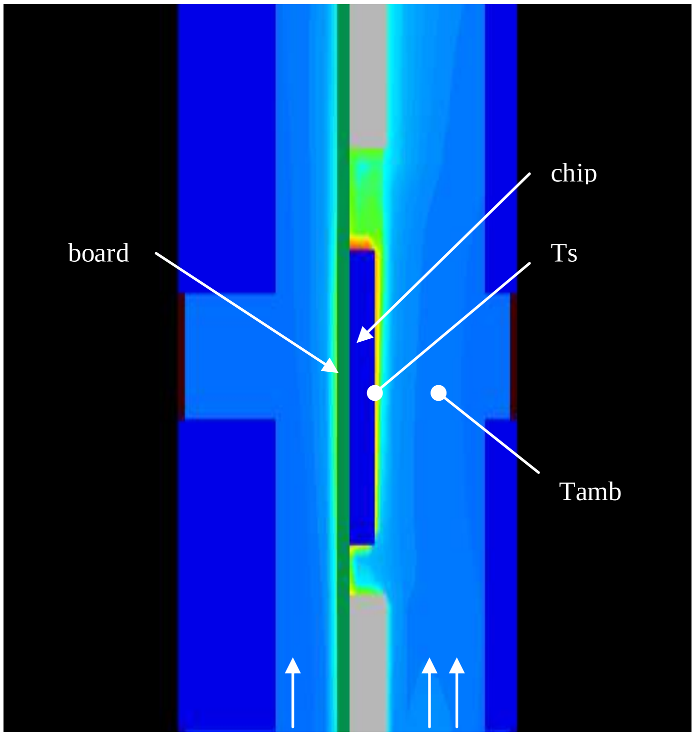
$$\frac{\Delta T_{\text{sea level}}}{\Delta T_{\text{alt}}} = \frac{\rho_{\text{alt}}}{\rho_{\text{sea level}}}$$

Hence, the flow rate remains approximately constant for the whole system as well as for the channels individually. The temperature increases as the inverse ratio of densities from sea level to the altitude condition in question. The results of the analysis are shown in Table 1.

			CFD ANALYSIS RESULTS		*Calculated*	*% Error*
TOP SHELF	**Volume in (cfm)**	**Delta T (deg C) TOP SHELF**	**Rack Delta T @ SL(deg C)**	**Rack Delta T @13k ft (deg C)**	**Delta T @13k = Delta T @SL*Density Ratio**	
Card1	16.74	0.50	6.83	9.78	9.65	-1.32%
Card2	29.55	1.09	8.79	12.72	12.41	-2.42%
Card3	11.53	1.43	8.94	12.57	12.63	0.42%
Card4	9.59	1.47	8.69	12.20	12.27	0.58%
Card5	9.11	1.25	7.60	10.60	10.74	1.33%
Card6	8.43	1.22	8.65	12.00	12.21	1.72%
Card7	8.56	1.66	7.47	10.35	10.54	1.89%
Card8	9.30	0.76	4.55	6.47	6.42	-0.83%
Card9	9.64	0.57	3.84	5.45	5.42	-0.63%
Card10	10.90	0.59	3.77	5.46	5.33	-2.38%
Card11	9.78	0.55	3.82	5.52	5.40	-2.15%
Card12	10.08	0.55	3.70	5.32	5.22	-1.81%
Card13	9.53	0.68	3.93	5.66	5.55	-1.88%
Card14	9.37	0.72	4.44	6.33	6.27	-0.85%
Card15	7.98	1.80	7.39	10.47	10.44	-0.30%
Card16	8.27	1.81	9.40	13.14	13.28	1.05%
Card17	8.57	1.91	10.07	14.06	14.22	1.15%
Card18	9.32	1.57	10.02	13.95	14.15	1.44%
Card19	10.75	1.69	10.16	14.28	14.35	0.49%
Card20	13.73	1.04	9.48	13.29	13.39	0.69%
Card21	16.17	0.74	8.75	12.25	12.35	0.84%
Card22	15.31	0.54	7.24	10.18	10.23	0.42%

TABLE 1

The zoom-in analysis results for a board component at sea level and 13,000 ft are shown in Table 2.



	Temperature [°C] Sea level	Temperature [°C] 13,000 ft
T_s	60.60	67.09
T_{amb}	29.36	31.55
ΔT_s	31.24	35.54

Based on Local T amb

	Temperature [°C] Sea level	Temperature [°C] 13,000 ft
T_s	60.60	67.09
T_{amb}	30.43	33.29
ΔT_s	30.17	33.80

Based on Tamb = T ave inlet to card

TABLE 2

29.36°C air @ 1.4 m/s

Alternately Use
Tamb = Tave inlet to card
This value can easily be calculated based on initial CFD results

Since we know that the approximate flow rates and velocities are similar at the two conditions, we try to use a flow over flat plate correlation to evaluate the effective heat transfer coefficient at those conditions. This is shown in Table 3. As can be seen from the results, using a flat plate correlation, over a Reynolds number of 2800 - 4000, the correlation yields results that are within 5.1% of the CFD results previously discussed.

Correlation between HEAT TRANSFER COEFFICIENT and ALTITUDE

Calculations made applies to laminar flows;

The following values were used to observe the 600LBGA

FLUID:	AIR		
Length, L:	0.045	m	input value
Surface Temperature, Ts:	333.6	°K	input value
Ambient Velocity, V:	1.4000	m/s	input value
Ambient Temperature:	302.36	°K	input value
Thermal Conductivity, k:	0.0364	W/m-K	small variation w/r to altitude; assumed constant
Viscosity, mu:	1.84E-05	N-s/m^2	small variation w/r to altitude; assumed constant
Heat Capacity, Cp:	1.01E+03	J/kg-K	small variation w/r to altitude; assumed constant

Altitude [ft]	density, rho * [kg/m^3]	Re=(rho·V·L)/mu	Pr = (Cp·mu)/k	Nu=(0.664Re^(0.5))·Pr^(1/3) [above formula is used if Pr>0.6] **	*h=(Nu·k)/L* [W/m^2-K]	*HTC ratio h(sl) / h(alt)*
Sea-level	1.16140	3.98E+03	0.7000	37.178	30.073	1.000
13000	0.82245	2.82E+03	0.7000	31.286	25.307	1.188

* - density is based on the altitude.
** - Based on Laminar flow over flat plate
Fundamentals of Heat and Mass Transfer - F. P. Incropera, D. P. DeWitt

Sample Calculation $Q = h_{(13K)} \times A \times deltaT_{(13K)}$ for an altitude of 13,000 ft
$Q = h_{(SL)} \times A \times deltaT_{(SL)}$ for sea-level

$$deltaT_{(13K)} = deltaT_{(SL)} \times [\, h_{(SL)} \div h_{(13K)} \,]$$

or

CALCULATED HTC RATIO $\frac{h_{(SL)}}{h_{(13K)}} = \frac{deltaT_{(13K)}}{deltaT_{(SL)}}$

	CFD RESULTS			CALCULATED*		
	Ts [°C]	Tave [°C]	ΔT [°C]	Ts [°C]	Tave [°C]	ΔT [°C]
Sea Level	60.60	30.43	30.17			
13,000 ft	67.09	33.29	33.80	69.35	33.50	35.84
Error				5.12%		

TABLE 3

Sample calculation for determining the component surface temperature at 13,000 ft, $T_{S@13K}$:

HTC Ratio, $h_{(SL)} / h_{(13K)}$:	1.188
$\Delta T_{S@SL}$ (from the CFD analysis):	30.17 °C
$\Delta T_{S@13K} = \Delta T_{S@SL} \times [\ h_{(SL)} / h_{(13K)}\ ]$:	35.84 °C
$\Delta T_{amb@13K} = \Delta T_{amb@SL}$ [density ratio] :	10.50 °C
$T_{amb@13K} = T_{amb}(23°C) + \Delta T_{amb@13K}$:	33.50 °C
$T_{S@13K} = T_{amb@13K} + \Delta T_{S@13K}$:	69.35 °C
$\%\text{Error} = \dfrac{(69.35 - 67.07)}{(67.07 - 23.00)} \times 100\%$:	5.2 %

The correlation can be based on both the local Tamb near the component or a reference Tamb at the inlet of the card in question. The above example was based on the Tamb at the inlet to the card and resulted in good correlation with CFD results. A similar calculation based on the local temperature near the component resulted in a slightly smaller error of the order of 4.3%.

Conclusions

The methodology described above provides a simple way to extract information from a sea level CFD analysis for estimating the system performance at altitude. Careful note should be made of the assumptions discussed prior to using this methodology. We have successfully used this technique in a number of cases to help our customers obtain a glimpse of the system performance at altitude.

Any questions you may have regarding this article can be submitted to Bruno Zoccali at bruno@tdmginc.com.

References

1. *Cooling Electronics at High Altitudes Made Easy, James Edwin Marthinuss Jr., George Thomas Hall, Electronics Cooling Magazine, Article in September 1998 issue.*

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3. *Incropera & DeWitt, Fundamentals of Heat and Mass Transfer, 4th ed.; John Wiley & Sons 1996; p.354*