A Figure of Merit Based Computational Heat Transfer Method for Aerothermal Analysis of Airborne Electronic System LRU

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***Abstract*—Aerospace technology is evolving at an unprecedented pace. Modern aerospace systems rely heavily on the capability of avionics system for operating various onboard systems such as communication, tracking, targeting propulsion, flight controls, etc. As power of electronics keeps increasing and the size continues to miniaturize the issue of high thermal fluxes becomes increasingly significant to flight vehicle designers. During design phase, this problem is often tackled by employing tedious computational techniques because generalized analytical solutions do not exist for specific airborne electronics scenarios. For this purpose, an alternative (novel) aerothermal assessment method is proposed using a Figure of Merit (FoM) based nominal fidelity empirical technique. The method is designed for the specific case of an electronics LRU placed in an unconditioned bay exposed to varying flight speeds and altitude regimes. The FoM terms are used to create a non-dimensional correlation between aerothermal design parameters and operating (flight) parameters. The aerothermal conjugate heat transfer analysis is then solved for constant speed with altitude variation to assess the effects on heat transfer coefficients as well as enclosure wall temperature. The results of FoM based empirical method show that the thermal analysis exhibit results that conform to the distinctive behavior in troposphere and stratosphere regimes. Moreover, the FoM based thermal analysis results appear to be in good conformance with high-fidelity CFD solutions.**

Keywords— aerothermal analysis, conjugate heat transfer, aerothermal figure-of-merit, avionics systems, unconditioned bay, altitude variation, empirical correlations

I. INTRODUCTION

The past two decades have witnessed unprecedented growth in aviation technology. With the advent of each new technology the power density of electronics systems also gone through an evolutionary change. Recent industrial trend is indicative of a three-fold increment in heat loads coupled with an equal reduction in aircraft mass. For decades the cooling of airborne electronics has relied on conditioned air obtained through heat exchange of compressor bled air. As aerodynamic performance of aircraft has improved bleeding of compressor air or placement of ram-air ducts on aircraft is no longer considered a viable option. The continuing increment in heat flux of avionics thus poses a serious issue for both avionics system and flight vehicle designers.

The cooling of airborne electronic systems' components has thus gained renewed attention and is being applied through configurations along various schemes. In majority of air-cooling applications, the electronic systems are provided with vents or opening within enclosures. The required air is drawn in from outside using fans or blowers. At present two types of housing configurations are in use and these imply two cooling approaches, for most closed-box applications the use of additional heat exchange devices is a method called *active cooling*. While for applications using open box approach or moderate cooling needs the manipulation of material properties serves as *passive cooling* technique. On the issue of cooling flow, the, the cooling flow field could be pre-designated hence classified as conditioned flow or can be exposed to free stream flow conditions thus referred to as unconditioned flow. The unconditioned bays are defined as those enclosures that house electronics (avionics) systems' LRUs and are cooled by air that is subject to mass and energy exchange between enclosure and free stream air flow [1]. Regardless of the flow and bay configurations, the cooling of electronics systems' LRU pose a unique problem especially for electronics components placed in unconditioned bays the fluid-structure interaction leads implicitly to conjugate heat transfer mechanisms often involving all the modes of transference. This scenario implies that each electronics LRU cooling is considered as a unique case and hence mathematically modelled to depict the specific physics of the problem.

II. PROBLEM SCENARIO

The LRU cooling inside the unconditioned bays is strongly dependent on heat transfer characteristics of atmospheric air for the convection and radiation modes [2]. As altitude increases, air density reduces, which in-turn decreases the convective heat transfer capability of the flow field. The cooling of avionics components placed inside the unconditioned bays depends mainly on the natural convection and radiation for the critical case where either no cooling fans are used or the forced cooling system has undergone a failure. In unconditioned bay areas the thermal transients are dependent on three fundamental parameters. These include:

i. Internal environment of bay area
ii. Cooling air temperature and thermal characteristics
iii. Temperature of electronics component

The internal environment of bay refers to bay ambient temperatures, pressures etc., the cooling air characteristics include temperature, pressure, thermal coefficient etc. of cooling fluxes while the thermal characteristics of electronics refers to bulk temperature of heat source and housing wall.

Figure 1 (below) refers to the problem scenario under consideration. For the generalized case a heat source comprising electronic system LRU is placed within a housing which in turn is mounted within an aircraft enclosure. The enclosure is cooled by freestream flow only. Whilst the aircraft traverses through various flight regimes the electronics LRU continues to operate steadily within the housing providing a 500W heat source which causes the aircraft enclosure walls to go through varying thermal cycles. This problem creates a complex thermal scenario comprising multi-mode conjugate heat transfer. The solution to this problem through closed form mathematical model is highly complex as well as recursive, involving single and double-segmented heat transfer approach [3] This itself is a tedious method especially in the early design stages. Thus, to make the solution method feasible as well as computationally efficient for early-stages of design process, the concept of design figure-of-merit for aerothermal analysis is introduced. The method is envisaged to use simple-as-possible variables to determine the enclosure wall temperatures as the aircraft traverses through various flight regime with the LRU system operating at 100% duty cycle. The wall temperature is significantly dependent on the ambient air conditions within the enclosure as well as housing. The ambient temperatures are subject to limits established under MIL-E-5400 [4]. Therefore, it is necessary for all avionics systems LRUs to satisfy the requirements prescribed by MIL standard.

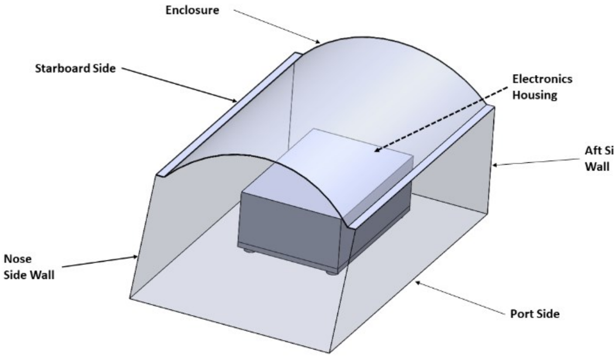

Figure 1: 3D model of electronics housing inside dorsal area

III. METHODLOGY AND MATHEMATICAL MODELLING

For the FoM-based conjugate aerothermal (heat transfer) analysis of LRU mounted on dorsal area, a two-step methodology is developed to verify the results with computational solution as well as conform the thermal design parameters of electronics bay with MIL-E-5400. A hypothetical case is solved for the LRU for specified design points at International Standard Atmosphere (ISA) 1976 [5] conditions. The solution approach is depicted at figure 2 (below). It is based on two fundamental steps that are as enlisted below: -

i. Step 1: Building a Non-dimensional figure-of-merit (FoM) and solving case scenarios for analytical solution.

ii. Step 2: Solving the case scenarios in Computational Fluid Dynamics (CFD) with conjugate heat transfer for verification of results.

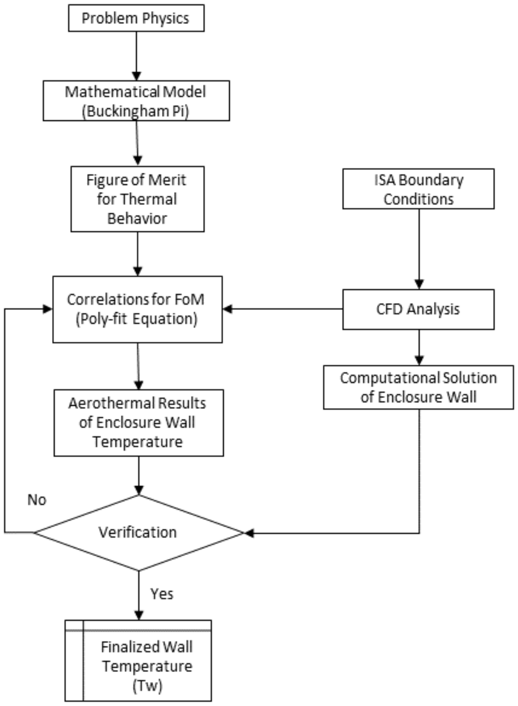

Figure 2: Process Flow Chart

A. Step 1 – The Figure-of-Merit Solution.

In non-dimensional analysis, an algorithm is developed as a user-friendly solution for the nominal fidelity assessment of thermal parameters from relation between different design and operating parameters of electronics equipment using the Buckingham pi theorem [6] . The purpose of non-dimensional analysis is the development of a figure of merit (FoM). The FoM is a decision making tool to determine the different alternatives for the aerothermal analysis. As Ali Sarosh [7] discussed that FoM is used for performance assessment of engineering system/sub-systems. It is developed for the pre-analysis of aerothermal thermal regimes before going into extensive computational analysis. For the development of FoM, a trade study is applied to evaluate the most suitable solution of proposed viable boundary conditions. This prevents from the effort of performing a detailed analysis of any alternative cases which does not meet the requirements of MIL-STD-5400. The trade study [7] for development of FoM is based on following characteristics:

1) Scope and Design Cases

Scope of the analysis is to calculate the aerothermodynamics parameters of the LRU for the dorsal mounted area of an airborne platform. Design cases are defined separately for boundary conditions pertaining to constant altitude and variable speed case.

2) Evaluation Criteria

For the aerothermal analysis of LRU, temperature of enclosure wall Tw is considered as an evaluation criterion. The temperature of enclosure wall is point of focus which depends on the temperature of electronics equipment housing.

For the mathematical modelling of aerothermal FoM, objective of the analysis and factors affecting or involved in achieving the analysis should be considered. Objective of analysis are the output parameter that are obtained after computational analysis. Factors affecting and factors involved for getting the objective are the input parameters and specific constants used in analysis. Dimensional analysis is a very important method to analyze physics of any problem. It is used to study the relation between the different parameters in any problem. Dimensional analysis is applied by using Buckingham pi theorem. The Buckingham pi theorem is applied to analyze the characteristics of different thermal parameters of electronics equipment (LRU). Two FoM are developed for altitude variation analysis.

In general, electronics equipment surface temperature is a function of: -

$$T_w = f_1(h_c, q'', V, \rho, \mu)$$

Where, hc is the heat transfer coefficient, V is the velocity, μ is the time, q'' is the heat source flux, ρ is the density of ambient and T_w is the wall temperature of dorsal area.

The number of physical variables, N= 6

The number of fundamental dimensions, K= 4. (i.e., mass, length, time, and temperature)

Thus, Number of Pi terms= N-K = 2

Considering: -

$$\pi_1 = f_2(T_w, h_c, q'', V, \mu)$$
$$\pi_2 = f_3(\rho, h_c, q'', V, \mu)$$

Solving: -

$$[MLT\theta]^0 = (\theta)^1(MT^{-3}\theta^{-1})^a(LT^{-1})^b(MT^{-3})^c(ML^{-1}T^{-1})^d$$

$$[MLT\theta]^0 = (ML^{-3})^1(MT^{-3}\theta^{-1})^a(LT^{-1})^b(MT^{-3})^c(ML^{-1}T^{-1})^d$$

Resulting Pi terms: -

$\boldsymbol{\pi_1 = \frac{T_w . h_c}{q''}}$	(1)
$\boldsymbol{\pi_2 = \frac{\rho v^3}{q''}}$	(2)

Where, π_1 is thermal design parameter and π_2 is operating parameter. Considering $\pi_1' = \frac{1}{\pi 1}$ & $\pi_2' = \frac{1}{\pi 2}$ for adjustment of order of the magnitude.

$$\boldsymbol{\pi'_1 = \frac{q''}{T_w . h_c}} \qquad \boldsymbol{\pi'_2 = \frac{q''}{\rho v^3}}$$

The scaling factor applied for both π_1 & π_2 to adjust the scale from 1 to 30. For π_1, scale factor of 400 and for π_2, scale factor of 40000 is used to adjust the magnitude up to tenth place.

$$\pi'_1 = \frac{q''}{T_w . h_c} \times 400$$
$$\pi'_2 = \frac{q''}{\rho v^3} \times 40000$$

$$\pi_1' = FoM\ 1$$

$$\pi_2 = FoM\ 2$$

The FoM 1 plot is generated using the enclosure wall temperature (Tw) results obtained from computational aerothermal analysis of LRU housing. A poly-fit equation is generated for FoM 2 as an input parameter and FoM 1 as an output parameter as depicted in Figure 3. The purpose of poly-fit equation is to develop a user friendly process for the calculation of enclosure wall temperature.

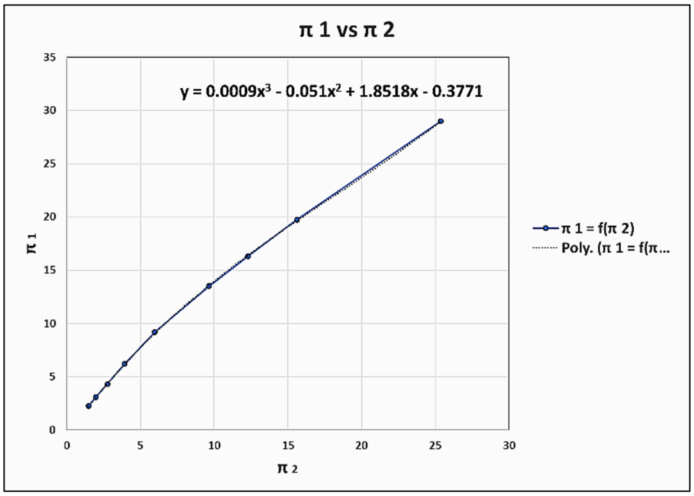

Figure 3:Poly-fit equation of FoM 1 vs FoM 2

The FoM correlation obtained from the ploy-fit curve is as follows: -

$$\boldsymbol{\pi_1' = a_1.\pi_2{}^3 + b_1.\pi_2{}^2 + c_1.\pi_2 + d_1} \tag{3}$$

Table 1: Constant parameters for Poly-fit equation

Constant Parameters	**Values**
a	9×10^{-4}
b	-5.1×10^{-2}
c	1.8518
d	-0.3771

FoM 2 evaluated at every altitude as mentioned in Table 2. The operating parameters are applied with respect to ISA 1976 specified atmospheric conditions.

Table 2: Operating parameters (FoM 2) at altitude variation

Altitude	$\boldsymbol{\rho}$ **(kg/m³)**	$\boldsymbol{h_c}$ **(W/m².k)**	$\boldsymbol{q''}$ **(W/m²)**	$\boldsymbol{V}$ **(m/s)**	$\boldsymbol{\pi_2}$
Sea level	1.225	610.8	987.9	280	1.469
10kft	0.9046	479.3	987.9	280	1.99
20kft	0.6526	369.1	987.9	280	2.75
30kft	0.4583	278.2	987.9	280	3.92
40kft	0.3015	199.0	987.9	280	5.97
50kft	0.1864	135.4	987.9	280	9.65
55kft	0.1466	111.7	987.9	280	12.27
60kft	0.1153	92.2	987.9	280	15.61
70kft	0.0709	62.5	987.9	280	25.39

B. Step 2 – CFD Based Aeothermal Verification of FoM Results

For the CFD, the aerothermal analysis is performed to evaluate the combined behaviour of conjugate heat transfer and radiation. The thermal management is evaluated at different altitudes up to 70kft to qualify for the conformance with FoM as well as MIL-STD-5400-E. According to different flight regimes of aircraft, characteristics of velocity and altitude are variable as well as constant under certain conditions. The CFD analysis is performed for constant velocity and variable altitude.

The mathematical model for the specified problem is not a straightforward case. The full range of 3D Navier Stoke Equation is used for incompressible flow domain[8]. But inclusive of viscous flow effect including viscous dissipation and turbulence is used for solving the aerothermal analysis with conjugate heat transfer. The energy equation is solved for the case of heat source (electronics housing) placed within the enclosure shell. Specie transfer is however not included as temperatures are well below the recovery temperature and flow velocities are also in lower to moderate Reynold number range. The continuity equation is used for evaluating the density variation because of altitude change for flight parameters of the aircraft. The continuity model is the applied inside the enclosure for incompressible flows. 3D-Momentum is used for modelling the enclosure's inside as well as the electronics equipment. The advection as well as viscous effect within and outside the electronics equipment is applied. Body force have explicitly been included to account for gravity effects for free convection outside the electronics equipment.

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho V) = 0 \tag{4}$$

Where ρ density is of fluid, V is the velocity in the x-direction and $\vec{\nabla}$ is the divergence, such that

$$\bar{V} = u\hat{\imath} + v\hat{\jmath} + w\hat{k}$$

$$\bar{\nabla} = {}^{\partial}/_{\partial x}\,\hat{\imath} + {}^{\partial}/_{\partial y}\,\hat{\jmath} + {}^{\partial}/_{\partial z}\,\hat{k}$$

Momentum Equation:

$$\frac{\partial V\rho}{\partial t} + \vec{\nabla}.(\rho V \times V) - \nabla(\mu_{eff}\nabla\vec{V}) = -\nabla p + \nabla(\mu_{eff}\nabla\vec{V}) + S \tag{5}$$

Where, V is the velocity, p is the pressure and μ_{eff} is the viscosity.

Turbulent Kinetic Energy Equation:

$$\frac{\partial}{\partial t}(\rho k) + \nabla(\rho V k) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla \mathrm{k}\right] + G_k + G_b - \rho\varepsilon \tag{6}$$

In these equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients. G_b, is the generation of turbulence kinetic energy due to buoyancy.

Turbulent Dissipation Equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla(\rho\varepsilon V) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla\varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{7}$$

The model constant $C_{1\varepsilon}$ and $C_{2\varepsilon}$ have been established to ensure that the model performs well for certain canonical flows. The model constants are $C_{1\varepsilon} = 1.44$ and $C_{2\varepsilon} = 1.9$. However, the degree to which ε is affected by buoyancy is determined by constant $C_{3\varepsilon}$.

IV. RESULTS AND DISCUSSION

The results for the aerothermal analysis of electronics equipment housing in unconditioned dorsal bay area are produced by using FoM based closed form analytical and computational analysis. The results are evaluated at ISA 1976 specified atmospheric conditions.

A. Figure-of-Merit Based Analytical Results

The FoM based closed form analytical results as described in Table 3 are obtained using the poly-fit equation for alternative altitudes at constant speed. The maximum temperature is 289.18K at the seal level and minimum temperature is 215.12K at 50kft.

Table 3: FoM based temperature results at altitude variation

Altitude	**Tw (K)**	**FoM 1**	**FoM 2**
Sea level	289.18	2.24	1.46
10kft	264.82	3.07	1.99
20kft	245.43	4.31	2.75
30kft	230.42	6.20	3.92
40kft	219.33	9.19	5.97
50kft	215.12	13.50	9.65
55kft	216.37	16.29	12.28
60kft	219.38	19.74	15.61
70kft	221.84	28.99	25.39

B. *Computational Fluid Dynamic (CFD) Analysis*

The results for aerothermal analysis of electronics equipment housing in unconditioned dorsal bay area are obtained using the ANSYS Fluent (ANSYS 19.2). The results are essentially built upon at ISA atmospheric conditions for 100% duty cycle of electronics equipment.

1) *ISA Boundary Conditions*

The ISA atmospheric conditions are changing with respect to change in altitude of the aircraft as mentioned in Table 4.

Table 4: ISA Boundary Conditions for CFD analysis

Altitude	**V (m/s)**	**ρ (kg/m^3)**	**C_p (J/kg.K)**
Sea level	280	1.225	1009
10kft	280	0.9046	1009
20kft	280	0.6526	1008
30kft	280	0.4583	1005
40kft	280	0.3015	1004
50kft	280	0.1864	1004
55kft	280	0.1466	1003
60kft	280	0.1153	1002
70kft	280	0.0709	1002

2) *Meshing*

Considering the simplicity of enclosure as depicted at Figure 4 and less computation time for analysis, structured mesh is used specifically for aerothermal analysis of LRU. Hexahedron element type is specified for this case. For the coordinate system of structured mesh, two types of coordinate systems are used namely, Cartesian, and curvilinear. Since the shape of LRU have curved surfaces, curvilinear body fitted coordinate system is used in structured meshing. A mesh independence study is conducted for grid convergence test to analyze the effect of mesh resolution on CFD results. To achieve mesh independence for optimal mesh, the mesh refinement is done by using a Grid Convergence Index (GCI) of 1.20 in the increasing order of magnitude by changing the number of elements along y-axis from 7 to 19, in region of electronics equipment housing.

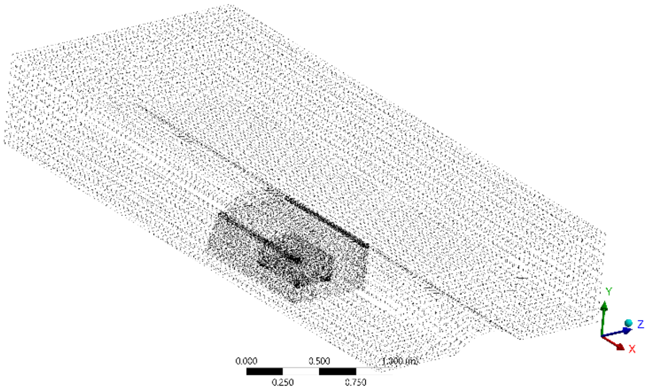

Figure 4: Optimal structured mesh

Table 5: Mesh Specifications

Mesh Parameters	**Values**
Mesh type	Structured
Element Size	50mm
Element Type	Hexahedron
Number of Nodes	57970
Number of Elements	79805
Discretization Scheme	Curvilinear body fitted
Elements on SDR (y-axis)	15

3) *Temperature Results*

The Figure 5 and 6 depicts the static temperature contours of enclosure wall i.e., Tw. The contours represent the case of conjugate heat transfer in multimode heat exchange scenario. The following general behavior of Tw as a function of altitude and speed changes under the ISA conditions is observed: -

i. The enclosure wall temperature at sea level is 288K and the minimum surface temperature is 215K at 50kft as mentioned in Table 5

ii. The heat transfer coefficients reduce with gain in altitudes. However, the reduction in temperature far exceeds that of heat transfer coefficient, thereby causing cooling to occur up to 40kft altitude

iii. The temperature of enclosure wall (Tw) reduces with gain in altitude up to 40kft and Tw, max drops to 216K (under ISA conditions). The enclosure wall temperature increases during flight through thermos-pause region to reach 218K at 70kft.

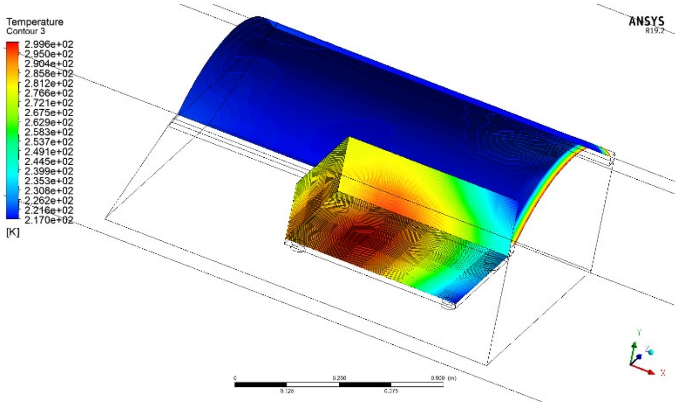

Figure 5: Temperature contours at 40kft

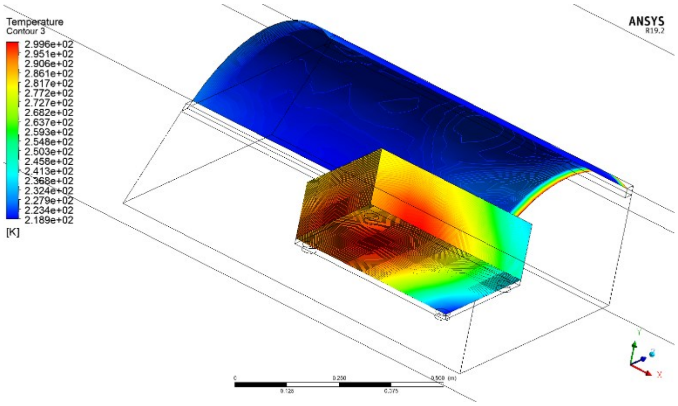

Figure 6: Temperature contours at 70kft

Table 6: CFD results at ISA conditions

Altitude	ρ (kg/m3)	Tw (CFD)
Sea level	1.225	288 K
10kft	0.9046	268 K
20kft	0.6526	248 K
30kft	0.4583	229 K
40kft	0.3015	216 K
50kft	0.1864	216 K
55kft	0.1466	217 K
60kft	0.1153	217 K
70kft	0.0709	218 K

C. Results Comparison

The results of FoM based analytical analysis are obtained using poly-fit equation (altitude variation) are compared with computational aerothermal results ae acquired using the ANSYS Fluent v19.2. Comparative temperature plots of Tw, max on enclosure wall show good conformance between results obtained from FoM and CFD analysis as depicted in Figure 7. Table 7 give the charts for the Tw, max on the enclosure wall as obtained from FoM and CFD Data. The overall error margin for all ISA altitude parameters being less than 2% is noted between the results obtained from FoM and CFD analysis.

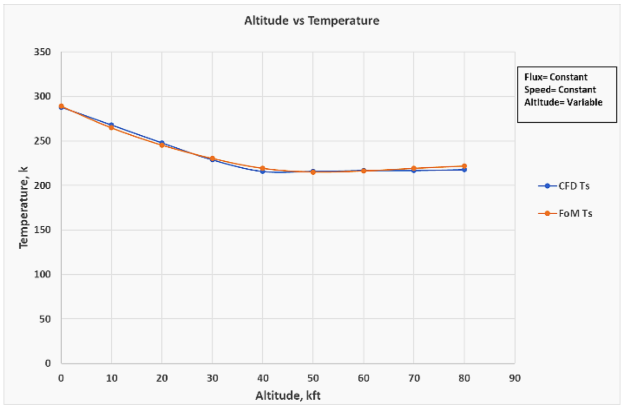

Figure 7: Result comparison plot of FoM and CFD

Table 7: Results comparison of FoM and CFD

Altitude	Tw (CFD)-K	Tw (FoM)-K	% Error
Sea level	288	289.18	0.409
10kft	268	264.82	1.1837
20kft	248	245.43	1.0333
30kft	229	230.42	0.6171
40kft	216	219.33	1.5215
50kft	216	215.12	0.405
55kft	217	216.37	0.2858
60kft	217	219.38	1.087
70kft	218	221.84	1.7353

D. Conclusion

The problem posed for the aerothermal analysis of the dorsal enclosure having the electronics housing has been addressed using the non-dimensional FoM as well as computational methods. The FoM approach is derived based on Buckingham pi theorem and poly-fit of FoM terms for constant speed and altitude variation. The CFD approach based on finite volume method is used for the verification of FoM results.

Aerothermal behaviors obtained by both approaches show that up to 40000 ft the surface temperatures of LRU and aircraft walls decrease with rise in altitude because the rate of decrease in atmospheric temperature exceeds that of the heat transfer coefficient. While in lower stratospheric regime (up to 70000 ft), the temperature for LRU and aircraft enclosure walls begin to increase primarily under the influence of thermal pause combined with reducing heat transfer coefficients. The maximum temperature is within the range specified by MIL-E-5400. Hence, thermal analysis of LRU satisfied the requirements of military standards. Results of FoM approach appear to be in good conformance with high-fidelity CFD solutions with an error margin of less than 2%.

The FoM-based method offers a fast and frugal approach to solving an otherwise complex aerothermal problem. novel method can thus significantly reduce the research efforts involved in employing tedious computational procedures for aerothermal analysis of airborne electronics.

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