A Minimal Input Dimensionless Empirical-Corrector (MIDEC) Method for Aerothermal Analysis of Airborne Electronics

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Abstract. Airborne electronics are designed to operate over a wide spectrum of flight conditions. This is much unlike ground-based electronics which operate at a constant altitude and within limited operating regimes. This makes airborne electronics far more challenging to design and analyze, especially from an aerothermal standpoint. With the modernization of the aviation industry, the LRUs of airborne electronics are continuing to miniaturize resulting in a manifold increment in their thermal flux. There is thus an ever-increasing need for performing thermal analysis of the electronics packages in-situ with the overall design process. The conventional analytical and computational thermal analysis methods for electronics are complex and highly recursive. This makes the early-on assessment of thermal parameters a major problem to reckon with during the conceptual design phase. In this paper, a novel approach for preliminary thermal analysis of airborne electronics has been proposed for the evaluation of temperature variations within a wide range of flight regimes. The Minimal Input Dimensionless Empirical-Corrector (MIDEC) method is developed that uses minimum fundamental operating and thermal variables to perform an initial assessment of temperature variations on aircraft surfaces, and housing electronics LRUs at different flight regimes. The results obtained from the MIDEC approach are assessed for a sample case scenario of electronics LRU installed on an airborne platform. Validation and verification of results exhibit a high degree of conformance between the MIDEC estimated results and those obtained through analytical and high-speed computational methods.

Keywords: Aerothermal Analysis; MIDEC Method; Airborne Electronics; Dimensionless Variable; Empirical Corrector; LRU Surface Temperature; Aircraft Enclosure Temperature.

1 Introduction

The continuing technological advancements in the aviation industry are leading to the miniaturization of avionics systems. Modern avionics is laden with high-end computing systems resulting in a substantial increment in the magnitude of heat flux from the components [1]. This makes the design phase of an avionics system a complex as well as a critical process for aerothermodynamist. The cooling of avionics system LRUs [2] inside the unconditioned bays is strongly dependent on the heat transfer characteristics of atmospheric air for the convection and radiation modes. The aerothermal analysis of airborne electronics is an analytically complex and computationally intensive process. For this reason, A novel algorithm named the Minimal Input Dimensionless Empirical-Corrector (MIDEC) is proposed for the fast and frugal evaluation of aerothermal parameters of aircraft electronics housing LRUs.

1.1 Problem Scenario

This paper considers the case of an electronics system LRU mounted in an unconditioned aircraft bay. Figure 1 depicts the LRU mounting inside the dorsal bay area. This area is being used for the placement of avionics components in an unconditioned environment whereby no free stream flow or conditioned air is available for the cooling process of avionics systems. Whilst the aircraft traverses [3] through various flight regimes the electronics LRU continues to operate steadily within the dorsal enclosure providing a heat rise that causes the aircraft enclosure walls to go through varying thermal cycles.

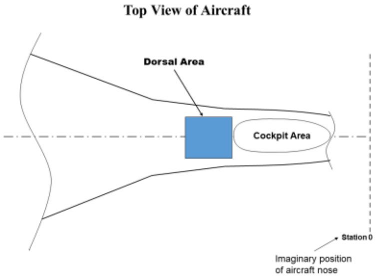

Fig. 1 *Orientation of dorsal area*

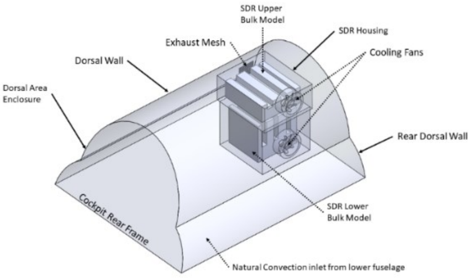

Fig. 2 *3D model of avionics system LRU*

For the simplification of the aerothermal analysis, a bulk heat source[4] is considered inside the LRU housing as depicted in Figure 2. The cooling fans are installed on the outer walls of LRU housing for the thermal management of internal components. The bulk model acts as the heat source such that heat is transferred to the LRU housing wall through combined radiation to free convection mode as depicted in Figure 3.

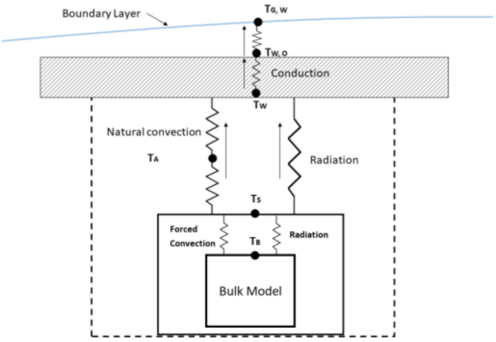

Fig. 3 *Electrical resistive analogy of avionics system LRU*

2 Development of MIDEC Algorithm

The MIDEC is developed through a three phase process. These includes: -

a) Phase-1: Generation of Archival Data Set
b) Phase-2: Derivation of MIDEC Math Model
c) Phase-3: Testing of MIDEC Algorithm

The generation of archival data set commence with input from flight regimes, flux, and geometry of avionics system. A computational solution is produced using CFD solvers. The data set of aerothermal design solution is stand as archives. The second step is the actual development of the MIDEC model. For the specified problem the selected design variables are evaluated for sensitivity till the most sensitive "Critical Parameters" are defined. The critical parameters are non dimensionalized for determining the unknown wall temperature. The result of Tw is then normalized to account for local derivates. The magnitude of derivatives is used for determining the correction factor needed to map the MIDEC solution onto analytical results. In the final step the MIDEC math model is tested by applying test case scenario and verifying the results with respect to analytical solution.

2.1 Phase 1- The Generation of Archival Anchor Data: -

Thermal Loading

$$100W \leq P \leq 500W$$

$$10\% \leq Duty\ Cycle \leq 100\%$$ (critical)

Operating Conditions

$$0.3 \leq M \leq 1.4$$

Solver Modes

- Combined: - Conduction, Convection, and Radiation
- Conjugate Heat Transfer

Material of Electronic LRU

AL 2024-T3
Enclosure Thickness= 1.8 mm

Material of Electronics LRU Housing

AL 7075- T6
Housing thickness= 1.2 mm
Emissivity = 0.6 (LRU housing)

Fan Parameter of Cooling Fan

24 CFM
Buoyancy Factor= 0.6 (natural convection)

Setting for Numerical Simulation (Pre-Processing):

Steady State: $T_{equip} = T_{max}$
Turbulent Model SST $K - \omega$ (Conjugate Thermal Fluid)
Radiation S2S (Combined Convection and Radiation)

Optimal Mesh:

Element Size = 11 mm
Number of Elements= 2758683

Setting for Numerical Simulation (Pre-Processing): Variation in ambient Condition from Troposphere to Stratosphere and fixed flight Mach number.

2.2 Phase 2- Derivation of MIDEC Math Model: -

Concept:
Aerothermal parameters of airborne electronics LRUs can be determined with reasonable accuracy by using algebraic correlations that use simple-as-possible inputs. The correlations must be adjusted to satisfy numerical as well as analytical solutions to hold good and wide range of input variables.

Steps to Implementations:

1) Selection of problem specific simple-as-possible (SAP) variables
2) Performing sensitivity analysis to determine the most critical SAP variable.
3) Non-dimensionalize the critical variables
4) Initialize the solution (using the anchor point from archived data)
5) Normalize the MIDEC results to adjust for wide range of applications.
6) Determine difference between MIDEC results and numerical simulations.
7) Determine the corrector factors (for mapping of results)
8) Adjust weights and finalize the MIDEC math model.

Selection of SAP Variables and Sensitivity Analysis:
The evolution of MIDEC math model commences with the identification of seven fundamental variables of aerothermal design problem. These include the heat transfer coefficient of convection, thermal conductivity of LRU surfaces, emissivity of LRU surfaces, flight speed, material density, heat flux and viscosity. The selection of variables is defined by sensitivity analysis by determining the precise variables that have the maximum effect on the outcome of aerothermal design solution as depicted in Figure 4.

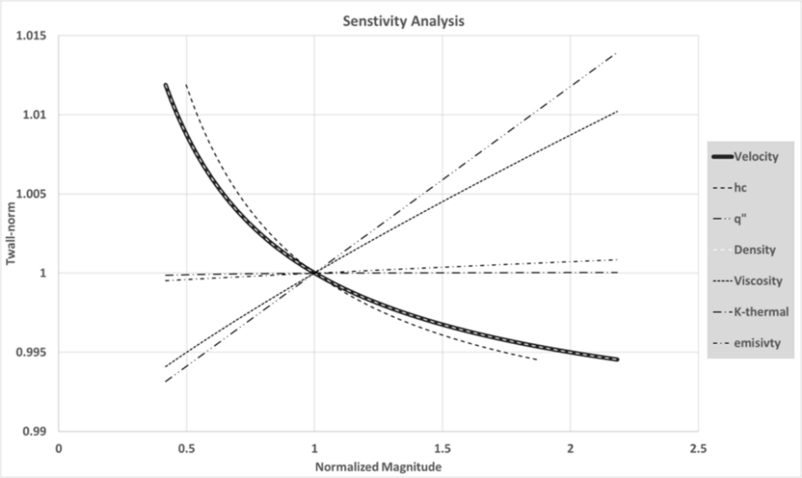

Fig. 4. *Sensitivity analysis of thermal and operating parameters*

The input and output variables have been normalized using the relation as follows: -

$$X_{norm} = \frac{X_i}{|X_{max}|_{D_1}} \tag{1}$$

$$where\ D_1 = \{X_i | X_{i+1} = \pm 0.05X_i\}$$

$$Tw_{norm} = \frac{Tw_i}{|T_{wmax}|_{D_2}} \tag{2}$$

$$where\ D_2 = \{Tw_i | Tw_1 < Tw_2 < Tw_n\}$$

Where X represents each of the representative sensitivity variables. The variables $h_c, q"_s, V_\infty, \rho_\infty, \mu_\infty$ appears to exhibit significant influence on the wall temperature of the flight vehicle.

$$T_w \approx f_1(h_c, q"_s, V_\infty, \rho_\infty, \mu_\infty)$$

In this case, all the fixed variables are extremely trivial to setting up of the aerothermal design problems and in most instances are well known at the start of the algorithm.

Non-Dimensional Variables:

The non-dimensional variables are developed for comparative assessment. These variables operated as Simple-as-Possible input variables.

$$\Pi_1 = w_1\left(\frac{1}{\pi_1}\right) \tag{3}$$

$$\Pi_2 = w_2\left(\frac{1}{\pi_2}\right) \tag{4}$$

Where w1 and w2 are arbitrary adjustment weights for adjusting the order of magnitude. Π_1 is the 1st FoM which represents the effect of thermal parameters on enclosure wall. Π_2 is the 2nd FoM which represents the effect of operating parameters on enclosure wall. Since flight parameters are independent of the parameters. Thus, thermal outcomes of enclosure LRU depends significantly on the operating conditions of flight vehicles.

$$\Pi_1 = f_4(\Pi_2)$$

$$\Pi_1 = 0.0009(\Pi_2^3) - 0.05(\Pi_2^2) + 1.8518(\Pi_2^1) - 0.3771 \tag{5}$$

Equation 5 is applicable for range of altitudes between sea level to 50,000 ft for the specific conditions that flight speed and thermal load remain constant at 280m/s and 260W respectively. This limitation must be overcome if the mathematical model must be used for a wide range of operating and thermal conditions. However, in order to keep the solution methodology as linear as possible for avoiding undue mathematical limitation leading to computational inefficiency, the normalization of variable is applied i.e., $T_w \rightarrow T_{w,norm}$ by using a normalization variable K_{Tw} such that.

$$K_{Tw} = \frac{T_w.V_\infty}{q_s} \tag{6}$$

Where T_w, V_∞, q_s are used from Π_1 & Π_2 values for the general range of altitudes. This implies that $K_{Tw} = K_{Tw}(h_\infty)$. Such that,

$$\overline{K_{Tw}}\,|_{h<10800m} = 2.997 \times 10^{-10}h^3 - 5 \times 10^{-6}h^2 + 0.0207h + 235.93 \tag{7}$$

$$\overline{K_{Tw}}\,|_{h>10800m} = 7.000 \times 10^{-12}h^3 + 3 \times 10^{-7}h^2 - 0.0092h + 259.57 \tag{8}$$

For the adjustment of thermal parameter values, a correction factor δ_{Tw} is developed as shown in Equations 11 and 12. The slope m1 and m2 (mentioned in equation 14) are calculated for the troposphere and stratosphere region as a function of ψ mentioned in equation 13. The constant parameter C as mentioned in Equations 11 and 12 is adjusted using the weight factors w_{cor}. The poly-fit equation of w_{cor} is generated as shown in equation 15.

$$\delta_{Tw} = f(H, m, w_{cor})$$

$$\delta_{Tw} = -m.(H) - m.(300) + C.w_{cor} \tag{9}$$

$$\delta_{Tw} = -m.(H) - m.(10800) + C.w_{cor} \tag{10}$$

Where: $C = T_{ref} \mid_{ISA=288K}$, $m = f(\psi)$, $\psi = \frac{V}{Q}$

$$m = a.\psi^4 + b.\psi^3 + c.\psi^2 + d.\psi + e \tag{11}$$

$w_{cor} = f\left(\frac{V}{Q}\right)$

$$w_{cor} = a.\psi^4 + b.\psi^3 + c.\psi^2 + d.\psi + e \tag{12}$$

***Table 1**: Constant Parameters*

Constant Terms	**m**		W_{cor}	
	S.L to 10.8km	**10.8km to 15km**	**S.L to 10.80km**	**10.8km to 15km**
a	-0.002743	0.008643	0.05645	0.1593
b	0.01042	-0.03279	-0.2145	-0.6052
c	-0.01382	0.04339	0.2852	0.8036
d	0.005477	-0.02406	-0.2005	-0.472
e	0.004541	0.005134	1.031	0.8608

Finally, using the mean K_{Tw}, instantaneous heat source, and velocity with the addition of corrected factor δ_{Tw}, the empirical relation for corrected wall temperature Tw_{cor} is developed. the empirical function can be used to estimate enclosure and LRU surface temperature in a fast and non-recursive manner.

$$T_{w-cor} = \frac{\bar{K}_{Tw}.Q_{inst}}{15.V_{inst}} + \delta_{T_w} \tag{13}$$

Testing of MIDEC Algorithm. After the MIDEC development phase, the algorithm is evaluated by solving it for different case scenarios. For the testing phase, two cases are considered of LRU mounted in the dorsal area of the aircraft. A bulk heat source of 500W and 750W is assumed for both cases, respectively. for the heat source of 500W and 750W, an arbitrary velocity of 80m/s and 320m/s is considered.

Solution Methodology for MIDEC Algorithm: In this section, the MIDEC algorithm solver steps are as follows: -

Step 1. Initialize the MIDEC Algorithm

Step 2. Input the altitude of the aircraft to compute the value of Kappa K_{Tw} at the respective altitude.

Step 3. Calculate Tw initialization using the value of Ktw.

Step 4. Calculate the ψ parameter.

Step 5. Using the ψ parameter, solve the slope parameter m and correct weight W_{cor}

Step 6. Input the slope and weight parameter for calculation of δ_{Tw}

Step 7. Compute the corrected value of temperature Tw_{cor} by addition of temperature deviation and initialized temperature.

3 Results

For a solution to the MIDEC algorithm, It is evident from the results obtained by solving the MIDEC algorithm that the behavior of Tw is nearly identical to actual calculations performed by computational and closed-form analytical solutions at a complete flight regime.

***Table 2**: Results: MIDEC and Actual Results*

Altitude (m)	CASE # 1			CASE # 2		
	MIDEC Results	**Actual Result**	**Error %**	**MIDEC Results**	**Actual Result**	**Error %**
0	283K	286K	1.04	285K	288.30K	1.13
2500	271K	273K	0.73	277.08K	273.18K	1.42
3500	264K	265K	0.37	270.24K	267.55K	1.00
4500	258K	259.9K	0.73	264.39K	261.94K	0.93
6000	248K	250K	0.8	254.01K	252.65K	0.53
8000	235K	236K	0.42	241.47K	239.81K	0.69
10000	223K	225K	0.88	227.63K	229.01K	0.59
12000	219.76K	219.74K	0.0091	224.09K	223.32K	0.34
15000	219.91K	219.92K	0.0045	226.49K	226.49K	0.0

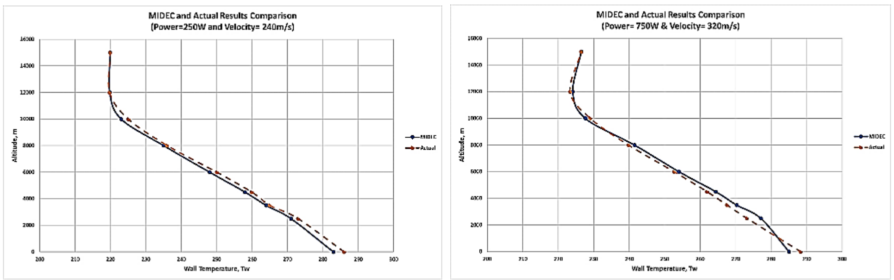

***Fig 5**: Result Comparison Plots (Case 1&2)*

Sensitivity Analysis of MIDEC. The FoM for the MIDEC algorithm is dependent on arbitrary weights. Therefore, sensitivity analysis is mandatory for the assessment of variable weights and order of magnitude for each FoM. It is evident from the analysis that the order of merit for FoM remains constant when arbitrary weight values are varied within the limits suggested in NAS 2006 manual. Hence, the weights do not affect the overall outcome of order-of-merit of aerothermal parameters as depicted in Figure 6.

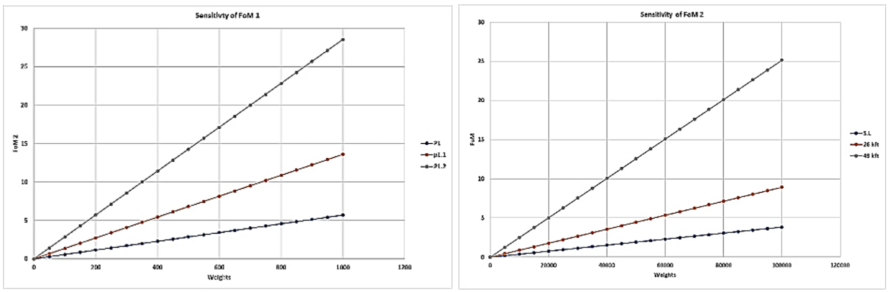

Fig 6: *Sensitivity of FoM 1 and FoM 2*

3.1 Conclusion

The problem posed by the aerothermal analysis of electronic LRU mounted inside the unconditioned bay of a dorsal enclosure has been addressed by developing a novel high-fidelity, preliminary assessment method - "The MIDEC" algorithm. The algorithm works satisfactorily for solving aerothermal problem of unconditioned airborne electronics by using the minimal input variables. The dimensionless groups of Π_1, Π_2 are well suited to effectively represents the physics of flow field. The qualitative behavior of MIDEC results in good conformance with aerothermal behavior of unconditioned surfaces, transitioning through the atmosphere. The quantitative behavior of MIDEC algorithm is assessed by solving two arbitrary cases. Results of the MIDEC algorithm appear to be in good conformance with high-fidelity CFD solutions with an error margin of less than 2%. The MIDEC algorithm thus offers a fast and frugal approach to solving an otherwise complex aerothermal problem. This novel method can thus significantly reduce the design efforts involved in employing tedious computational procedures for the initial assessment of aerothermal analysis of airborne electronics.

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