Systems Radiation Consideration for Thermal Risk Assessment of Avionics Bays in Conceptual Design

Tanmay Bhise*, Florian Sanchez**, Susan Liscouët-Hanke***

Department of Mechanical, Industrial and Aerospace Engineering
Concordia University, Montreal, Quebec, H3G1M8, Canada
*Research Assistant, **Post-Doctoral Fellow, ***Associate Professor

Abstract

Thermal analysis in conceptual design helps prevent the risk of discovering thermal issues too late during the development of a new aircraft, which may lead to major costly modifications and delays for aircraft manufacturers. A so-called Thermal Risk Assessment (TRA) approach was developed recently, adapted to aircraft conceptual design. The TRA considers ventilation, stratification, and mainstream flow analysis for thermal risk assessment of aircraft systems. However, thermal radiation considerations in this approach are limited. This paper presents an investigation of the influence of heat radiation on system thermal risk for tightly packaged equipment bays, using computational fluid dynamics (CFD) simulation. As such, this paper presents the first step for an improved TRA for tightly packaged avionics bays.

Nomenclature

Abbreviations

CFD	Computational Fluid Dynamics
MCU	Modular Concept Units
SST	Shear Stress Transport
TRA	Thermal Risk Assessment

Symbols

ε	Thermal Emissivity
F	View Factor
J	Radiosity (W/m^2)
q	Heat Flux (W/m^2)
σ	Stefan-Boltzmann Constant (W/m^{2}K^4)
T	Temperature (K)

Subscripts

conv	Convection
i	First object index
j	Second object index
rad	Radiation
lim	limiting

I. Introduction

As the demand for sustainable aviation grows, aircraft manufacturers investigate more electric, hybrid-electric, and all-electric aircraft concepts. With embedded power increasing in these novel concepts, thermal considerations are becoming more critical. In developing these innovative designs, aerospace companies continuously aim to improve and streamline their development processes. Among such efforts is integrating detailed design studies into the conceptual design, aiming to reduce the discovery of issues too late, resulting in costly design changes and development delays. One example is thermal analysis, for which recent efforts have been made in collaborative research, as presented in [1]. In particular, a novel thermal risk prediction approach was developed by Sanchez and Liscouët-Hanke in [2].

"Thermal risk" is defined as the potential of non-compliance with thermal requirements (e.g., exceeding maximum allowable skin temperature of a component or exceeding maximum allowable bay temperature) [2]. The existing Thermal Risk Assessment (TRA) methodology consideration consists of the step-by-step analysis of aircraft-level aspects and system-level aspects, using dimensionless numbers considering ventilation, stratification, and mainstream flow analysis. This TRA is implemented into the Python computing environment, the pySysTher tool, using a penalty-point approach to evaluate thermal risk [3].

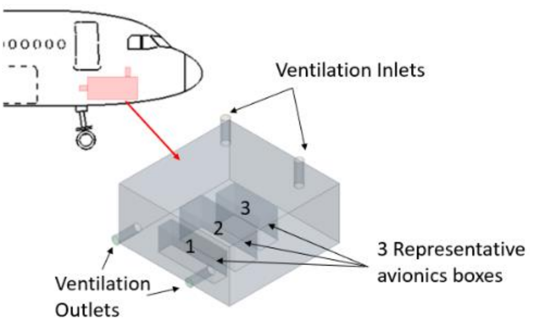
The validation of the TRA presented by Sanchez et al. in [3] shows that in tightly packaged avionics bays, the TRA tends to overpredict the thermal risk for systems not engulfed by the mainstream flow. One reason raised by the authors might be that the current TRA has limitations on its thermal radiation consideration. For example, it considers radiative heat transfer between systems and bay walls only when the temperature of the bay wall is higher than the systems' permissible temperature limits. Therefore, this paper deals with the thermal radiation aspect of the equipment bay.

This paper investigates thermal radiation aspects using Computational Fluid Dynamics (CFD) simulations for two different aircraft equipment bays, as presented in Section II. Both equipment bays represent typical avionics bays in transport category aircraft. Following the CFD analysis, a computation of the thermal risk associated with the radiative aspects is presented in Section III and compared with the current TRA method. This extended abstract ends with a conclusion and the description of future work in Section IV.

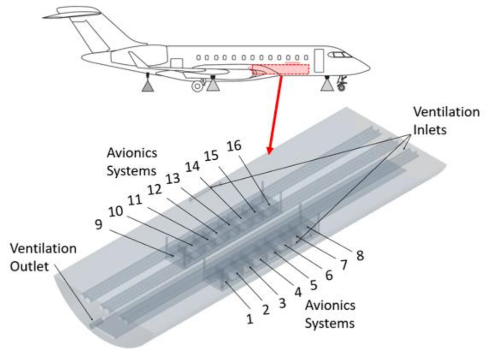
II. Investigation of the influence of heat radiation on thermal risk assessment

This paper investigates two questions regarding the radiative heat transfer between systems featuring high heat loads in tightly packed equipment bays. First, the significance of the radiative heat transfer is examined. Secondly, it is explored how the radiative heat transfer affects the thermal risk of the systems. These questions are assessed using CFD simulation for two different aircraft equipment bay configurations.

The first configuration is similar to a cockpit underfloor equipment bay of the commercial narrow-body, e.g., the Airbus A320, shown in Figure 1 (a). The objective of this CFD study is to investigate if radiation consideration is significant for thermal risk assessment. The second configuration is derived from a cabin underfloor equipment bay typically found in smaller business aircraft, e.g., the Bombardier Global 5000, depicted in Figure 1 (b). This second CFD study aims to examine the correlation between radiation heat flux emerging from the systems and their thermal risk.



a) Cockpit underfloor equipment bay in a larger commercial aircraft and derived simplified bay model with three cubic-shaped systems (Configuration 1)



b) Cabin underfloor equipment bay in a business jet and derived simplified bay model with 16 cuboid-shaped systems (Configuration 2)

Figure 1: Simplified avionics equipment bay configurations used for CFD studies.

The assumptions and models used for CFD simulations are as follow:

- Incompressible and ideal gas
- Gravity present
- Radiation heat transfer considered
- k-ε / SST k-ω turbulence models

The mesh of both bay configurations contains polyhedral cells due to their better numerical stability. Additionally, prism layer cells help to resolve boundary layers.

A. Significance of heat radiation inside an equipment bay

This CFD study helps to identify how thermal radiation impacts the system temperature and the overall thermal environment of the equipment bay. Therefore, it will play a key role in determining if radiation consideration is significant for thermal risk assessment.

For case study 1, shown in Figure 2 the ventilation air enters the bay from the cockpit through cockpit panels. Two electric fans assure the forced circulation of the cooled air. This air then flows under the cargo compartment with the help of outlet bypass valves [4]. Dimensions of the equipment bays are derived from the manufacturer's website [5].

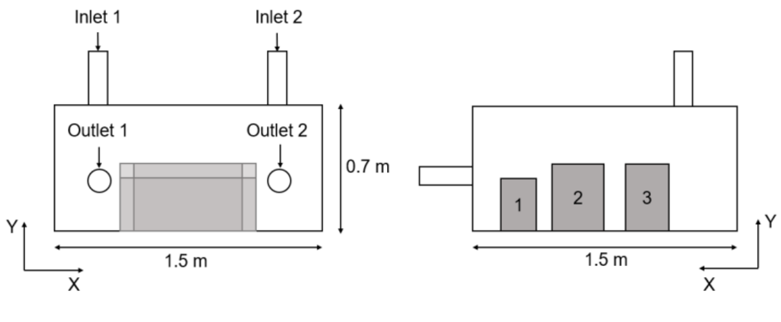


Figure 2: Simplified cockpit underfloor equipment bay with dimensions and air-inlet and outlet locations

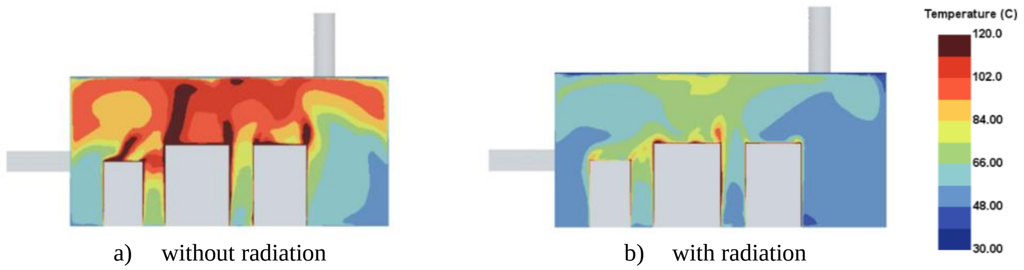
Table 1: Specifications of the representative avionics systems used in configuration 1 of the equipment bay

System number	Length (m)	Width (m)	Height (m)	Heat load (W)
1	0.76	0.18	0.3	1000
2	0.76	0.3	0.38	600
3	0.6	0.25	0.38	1000

This study considers three systems similar to previous work by Sanchez et al. [2], [3], based on standards used for avionics boxes [6], [7]. The heat load and system sizes are amplified by four times to amplify the effects of radiation. Table 1 summarizes the system specifications.

For this configuration, a worst-case hot day scenario with a ground-level ambient temperature of 55°C (at 1 atm) is considered. The top wall of the equipment bay is assumed to be cooler (30°C) than the bottom wall (55°C) to create an unstable thermal gradient for this study. The left wall of the equipment bay is assumed to be adiabatic; all the other walls of the bay are at 55°C. Systems considered in this case study have a temperature limit of 70°C, which requires a mass flow rate of 0.035 Kg/s-kW according to standards set by DO-160 [8]. Hence, to meet these standards, the total cooling mass flow rate is assumed as 0.0382 Kg/s. The outlets have a split ratio of 0.5 each. The temperature of the cooling air coming out of the inlet is assumed to be 30°C.

The CFD simulations show that the radiation has a significant impact on the system temperature and thermal environment of the equipment bay. Radiation considerably lowers the temperature of the systems as much as 60 % lower than the case without radiation. Moreover, the radiation heat flux contribution in total heat flux emerging from the systems is also substantial; it can be 50 % of the total heat flux. As shown in Figure 3, this radiation heat flux weakens the boundary layer emerging from the systems, resulting in temperature homogenization of the bay environment. In conclusion, this case study shows that radiation consideration cannot always be neglected.

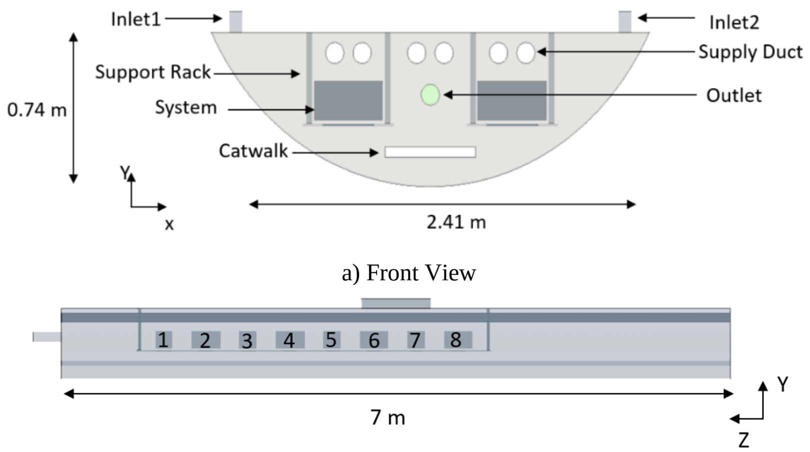


a) without radiation b) with radiation

Figure 3: Cockpit underfloor equipment bay temperature contour

B. Influence of heat radiation on thermal risk assessment

The CFD investigations in this section will examine the exact role of heat radiation in assessing thermal risk. For configuration 2, shown in Figure 4, the air enters the bay from the forward cabin exhaust (Inlet 1 and Inlet 2). This air is extracted via an avionics outlet fan (Outlet) to the forward outflow valve [9]. Moreover, flow also enters the equipment bay via the cockpit exhaust (Inlet 3). The dimensions of the bay are derived from the manufacturer's pilot training guide [10].



a) Front View

b) Side View

Figure 4: Simplified cockpit underfloor equipment bay with dimensions and air-inlet and outlet locations

Table 2: Specifications of the representative avionics systems used in configuration 2 of the equipment bay

System number	System Type	Length (m)	Width (m)	Height (m)	Heat load (W)
Odd numbered systems	2 x 3 MCU	0.38	0.18	0.19	300
Even Numbered Systems	2 x 5 MCU	0.38	0.3	0.19	500

This study considers Modular Concept Unit (MCU) systems similar to the ones used by Sanchez et al. [3] based on standards used for avionics boxes [6], [7]. Figure 4 (b) shows the placement of the systems, and Table 2 tabulates their specifications. As per MIL-STD-1472G standards, for ease of maintenance, the Minimum gap between avionics systems in avionics bays must be more than 0.045 m [11]. Therefore, a CFD study for three different gap sizes (0.05 m, 0.1 m, and 0.2 m) is performed. Table 3 shows the nine simulation cases and the associated variations in the boundary conditions.

Table 3: CFD analyses carried out for configuration 2 of the equipment bay

Cases	Mass Flow Rate (Kg/s)	Cases	System Gap (m)
1,2,3	0.07	1,4,7	0.05
4,5,6	0.14	2,5,8	0.1
7,8,9	0.27	3.6.9	0.2

Similar to Configuration 1, this study considers the ambient air temperature of 55°C (at 1 atm). The top wall is relatively cooler (30°C). The rest of the bay walls are hotter (55°C). Other objects inside the bay, such as the catwalk and the supporting rack, are considered adiabatic. This equipment bay configuration has three inlets and one outlet. The temperature of the cooling air is 30°C. Likewise, the supply ducts carrying cooling air to other parts of the aircraft are also at 30°C.

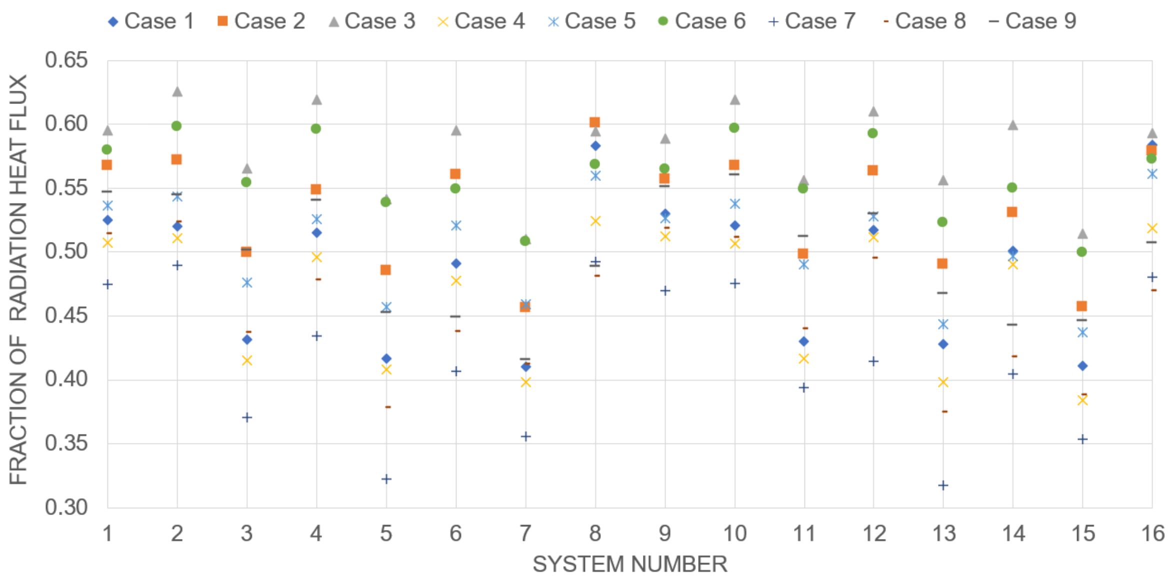


Figure 5: System boundary radiation heat flux

This case study reveals that the distribution of the cooling mass flow rate inside an equipment bay is important in determining the thermal risk of the systems. The thermal risk can be predicted by analyzing if systems lie on mainstream flow. A simplified mainstream flow analysis based on the location and geometry of the systems and the ventilation sources [3] is implemented in the existing thermal risk assessment tool, pySysTher.

As illustrated in Figure *5*, the contribution of the radiation heat flux is considerably high; it does influence the temperature of the systems, especially for the systems which do not lie on the mainstream flow in a highly packed equipment bay. Therefore, considering thermal interaction analysis in thermal risk assessment can help to determine the thermal risk of such systems. The following section discusses the proposed theoretical approach to account for thermal interactions inside an equipment bay.

III. Thermal interaction analysis

A. Proposed thermal interaction analysis approach

As a brief introduction to thermal interaction analysis, this approach requires the calculation of the limiting heat flux of a system when it operates at its thermal limit. The limiting heat fluxes are then compared with the actual heat fluxes of the systems. If the actual heat flux of the system is higher than the limiting heat flux, those systems can be potentially at high risk. Since this approach is for the systems which are not engulfed by the mainstream flow, the convection heat transfer between systems and the surrounding air is due to free (natural) convection. In addition, to account for radiation heat transfer, the so-called Radiosity Matrix Method is employed to estimate radiation heat fluxes [12].

The estimation of radiation heat flux is a two-step process. First, calculate radiosities (J) using Eq. (1). Here, T_{lim} is the maximum permissible temperature of the systems, ε is the thermal emissivity while σ is Stefan-Boltzmann Constant. This equation contains the view factor (F). Which can be obtained from view factor correlation or by methods such as Monte Carlo or adaptive integration method [13]–[15]. It should be noted that for adiabatic surfaces radiosity can be calculated by considering these surfaces as black bodies ($\sigma T_{lim_i}{}^4 = J_i$).

$$\sigma T_{lim_i}{}^4 = J_i - \frac{1-\varepsilon_i}{\varepsilon_i}\sum_{j=1}^{N} F_{ij}(J_i - J_j) \qquad (1)$$

The second step is to use radiosities obtained from equation (1) in equation (2) to calculate limiting radiation heat flux ($\dot{q}_{rad}$). For the adiabatic surfaces, radiation heat flux becomes zero ($\dot{q}_{rad} = 0$).

$$\dot{q}_{rad_i} = \sum_{j=1}^{N} F_{ij}(J_i - J_j) \qquad (2)$$

The overall limiting heat flux is calculated (by adding radiation and convection limiting heat flux) and compared with the actual heat flux of the system for thermal risk scoring, using rules mentioned in Table 4.

Table 4: Thermal risk scores for thermal interaction analysis

Condition	Thermal Risk
System heat flux < 0.8 (Limiting System heat flux)	low
(Limiting System heat flux) ≤ System heat flux ≤ 0.8 (Limiting System heat flux)	medium
System heat flux > (Limiting System heat flux)	high

B. Validation of the proposed thermal interaction analysis approach

A CFD study is carried out to validate the thermal risk prediction by thermal interaction analysis. For this study, the bay configuration is the cabin underfloor equipment bay, as used in section II (B). The geometry and boundary conditions are identical to Case 3. However, to account for the effect of heat flux on thermal risk, heat fluxes of the systems are varied from 500 to 800 W/m^2. For the validation, the view factors are obtained from the built-in calculator in Star CCM +. The convective heat transfer coefficient is assumed to be 5 W/m^2K. Table 5 compares the CFD results, and risk predicted by TRA.

Table 5: Comparison between CFD results and thermal risk assessment

System Number	Thermal risk from CFD analysis	Predicted risk w/o thermal interaction analysis	Predicted risk with thermal interaction analysis	System Number	Thermal risk from CFD analysis	Predicted risk w/o thermal interaction analysis	Predicted risk with thermal interaction analysis
1	Medium	High	Medium	9	Medium	High	Medium
2	High	High	High	10	High	High	High
3	Medium	High	Medium	11	Medium	High	Medium
4	High	High	High	12	High	High	High
5	Medium	High	Medium	13	Medium	High	Medium
6	High	High	High	14	High	High	High
7	Low	High	Medium	15	Low	High	Low
8	High	High	High	16	Medium	High	High

Table 5 reveals that thermal interaction analysis gives satisfactory results for 14 out of 16 systems. However, it predicts higher thermal risk for systems 7 and 16 compared to CFD. This is because of entrapped flow activities due to the closeness of these systems to the ventilation inlet. Overall, The results are still acceptable since these are conservative results.

IV. Conclusion and future work

The two CFD studies carried out in this extended abstract concludes that heat radiation has a significant impact on determining system thermal risk, especially for compact avionics bays. The thermal interaction analysis is proposed to enhance risk prediction capabilities for tightly packed avionics bays. This analysis is validated with a CFD case study consisting of systems with varying heat fluxes. For this case, it was found to give satisfactory results. Nevertheless, the view factors needed to calculate radiation heat flux are derived from third-party software. The next step will focus on computing view factors for thermal interaction analysis. Furthermore, this analysis will be applied to different configurations of the bays. The final validation will help to determine the efficacy of the thermal interaction analysis with radiation consideration.

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