




Article

Influence of Ventilation Flow Rate and Gap Distance on the Radiative Heat Transfer in Aircraft Avionics Bays

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Abstract: The feasibility of the future more-electric, hybrid-electric, and all-electric aircraft configurations will depend on a good understanding of thermal aspects early in the design. However, thermal analysis of aircraft equipment bays is typically performed at later design stages to validate if the design meets the minimal certification requirements rather than to optimize the cooling strategy. The presented work aims to provide new insight into thermal aspects in typical aircraft equipment bays. In particular, system thermal interactions, such as radiation, play a more significant role in tightly packaged bays, such as avionics bays. This paper investigates the influence of radiation on the overall system heat dissipation in two representative avionics bays. Using Computational Fluid Dynamics (CFD) simulation, combined with an analytical approach, the authors analyze the impact of several parameters, such as varying mass flow rates and distances between adjacent systems, on their thermal interaction. The results suggest that the radiative effects must be considered when the gap distance between the systems is larger than 0.1 m, the flow rate between two systems is not strong enough to have high convective heat exchanges, when the systems of interest are hidden by other systems from the ventilation sources, and when the system's internal heat dissipation is significant. Overall, this paper's results will contribute enhance conceptual design methods, such as the previously developed Thermal Risk Analysis, and help optimize thermal management strategies for future aircraft.

Keywords: thermal analysis; aircraft thermal management; heat radiation; avionics bay; computational fluid dynamics (CFD); ventilation strategy; system integration



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1. Introduction

Aircraft systems operate in a very challenging thermal environment. While outside temperatures can be between $-70\text{ }^{\circ}\text{C}$ to $+55\text{ }^{\circ}\text{C}$, unpressurized equipment bays may have even higher temperature ranges. Traditionally, most electronic equipment (also called avionics boxes) is installed in pressurized or ventilated zones. In commercial and business aircraft, these equipment bays are typically ventilated through the aircraft environmental control systems (ECS). Equipment bays generally are tightly packed to minimize the space required, leaving usable space for passengers or other payloads. In addition, the ventilation should ideally be kept to a minimum, not penalizing the ECS and thus the overall aircraft weight, drag and power consumption.

The thermal analysis of equipment bays is typically challenging, as it requires detailed information about the geometry, system operation and heat loads, and the potential ventilation system supply. Hence, aircraft thermal analyses are carried out later in the design stage when bay architecture is well defined. Therefore, any thermal issues discovered late in the development of a new aircraft may lead to major costly modifications and delays in the development cycle. The thermal analysis of aircraft equipment bays is typically

performed to validate if the design meets the minimal certification requirements rather than optimizing the cooling strategy or the system placement upfront in the conceptual design. A non-optimal aircraft design is against the aim of reducing the environmental footprint of future aircraft.

The importance of thermal considerations, particularly for future aircraft, has been recently exposed in a review paper by Van Heerden et al. [1]. The current literature on thermal analysis in aircraft focuses mainly on passenger cabin studies [2,3]. Butler et al. [4–6] published work for the aircraft crown area. With the advent of more electrical actuator technologies, several researchers focused on this particular aspect [7–9]. Also, recent literature discusses details about battery thermal management for hybrid or all-electric aircraft [10]. Sanchez et al. [11] formulated the need for a multi-level approach to improving thermal analysis throughout the development process of future aircraft to meet the need to introduce thermal analysis earlier in the development cycle. In particular, the authors developed a so-called thermal risk assessment (TRA) methodology suitable for conceptual design [12,13].

The prior work shows a knowledge gap for the thermal interactions occurring in typical tightly packed aircraft equipment bays. In particular, system thermal interactions, such as radiation, may play a more significant role in tightly packaged avionics bays [13,14]. In addition, mixed convection regime exists when the equipment bay's ventilation flow rate is not strong enough to compete against buoyancy effects. The effect of radiation on mixed convection cooling of a ventilated cavity with multiple openings has been studied by Ezzaraa et al. [15]. One of the study's findings is that increasing radiation leads to a hotter environment in the cavity in the case of a mixed convection regime, while in the forced convection regime, increasing radiation has a positive effect on the cooling process.

Therefore, this paper aims to study the effects of radiation on more complex geometrical configurations such as aircraft equipment bays. The authors investigate the influence of radiation on the overall system heat dissipation in two representative avionics bays, depicted in Figure 1, using computational fluid dynamics (CFD). The aim is to gain knowledge about the conditions, which requires considering radiation in a conceptual design context, such as the TRA mentioned above. Section 2 presents the assumptions, analyses and results for Configuration 1 and 2. The influence of gap width and ventilation flow rate is investigated using a parametric study. In addition, an analytical method is used to analyze the thermal interactions better. Section 3 summarizes the findings and recommends the following steps to improve current conceptual design methods.

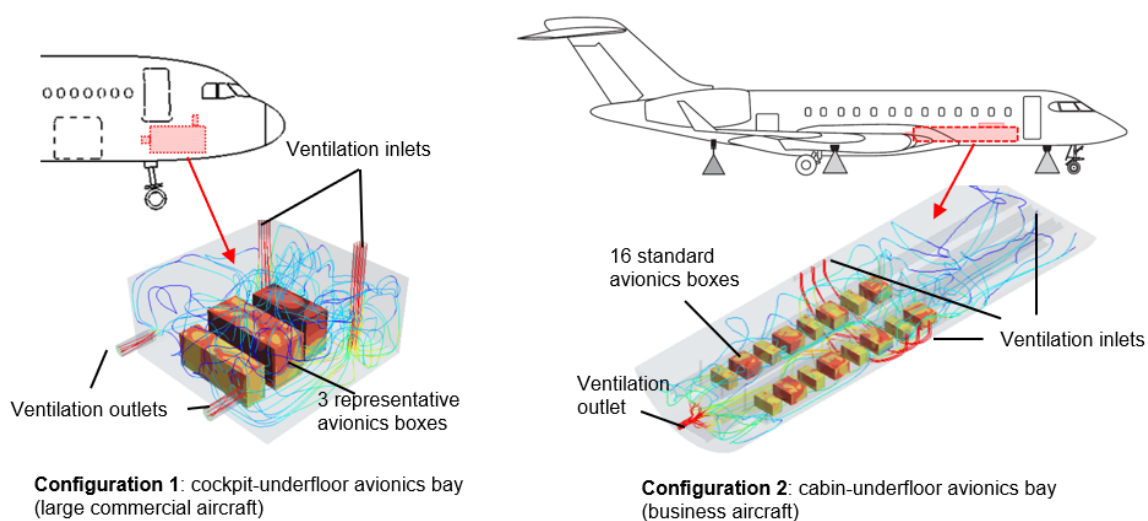


Figure 1. Aircraft avionics bay configurations for the investigation of the thermal radiation aspect.

2. CFD Studies to Investigate the Influence of Heat Radiation on Aircraft Thermal Behavior

This CFD study investigates whether the influence of heat radiation inside an equipment bay is significant. The analyses carried out deal with two avionics equipment bay configurations:

- A cockpit underfloor equipment bay, representative of a commercial narrow-body aircraft, such as the Airbus A320 (Figure 1, Configuration 1).
- A cabin underfloor equipment bay, representative of a business aircraft, such as the Bombardier Global 5000 (Figure 1, Configuration 2).

2.1. Description of the Cockpit-Underfloor Avionics Bay (Configuration 1)

This first configuration deals with the cockpit underfloor equipment bay of a commercial aircraft. The CFD study highlights the influence of heat radiative exchange on avionics equipment by comparing the cockpit underfloor thermal environment with and without radiation.

This type of avionics ventilation system is typically fully automatic and controlled by an avionics equipment ventilation computer. The ventilation air enters the bay from the cockpit through cockpit panels that use two exhaust fans. This air is then passed to the space under the cargo compartment with the help of an outlet bypass valve.

The approximate dimensions of the equipment bays are derived from the drawing of the aircraft available on the Airbus website [16]. Notice that the geometry of this equipment bay has been simplified and is depicted in Figure 2.

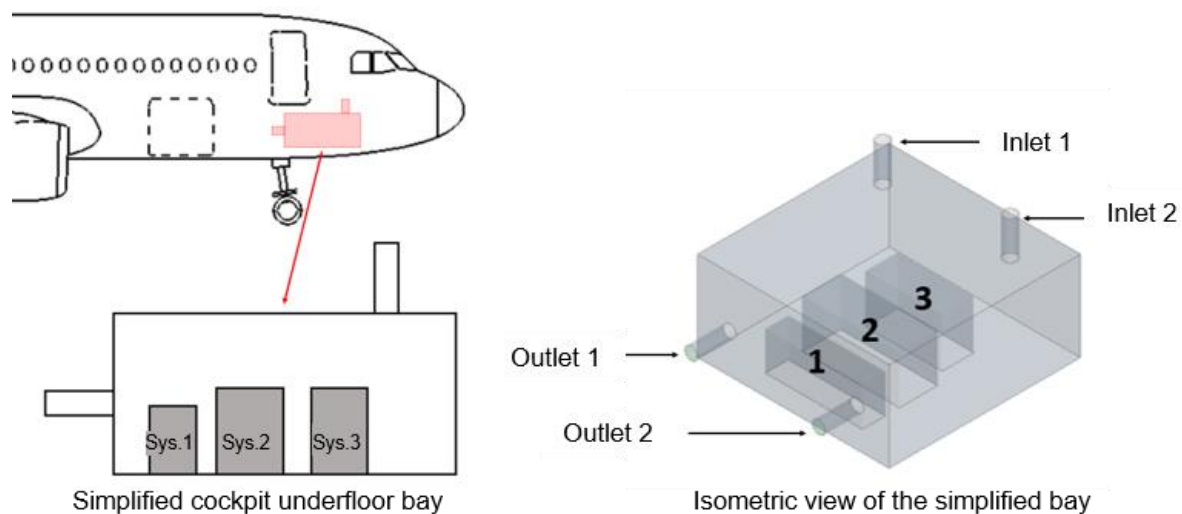


Figure 2. Cockpit underfloor equipment bay in a larger commercial aircraft and derived simplified bay model with three cubic-shaped systems (Configuration 1).

This study considers three systems similar to those used in previous work [12,13]. The first system is analogous to a High Voltage Power Supply (HVPS) with a heat load of 1000 W. Whereas System 2 and System 3 are assumed to be systems of the type “5 MCU” (Modular Concept Units) and type “3 MCU” with heat loads of 600 W and 1000 W, respectively. Figure 3 summarizes the system specifications.

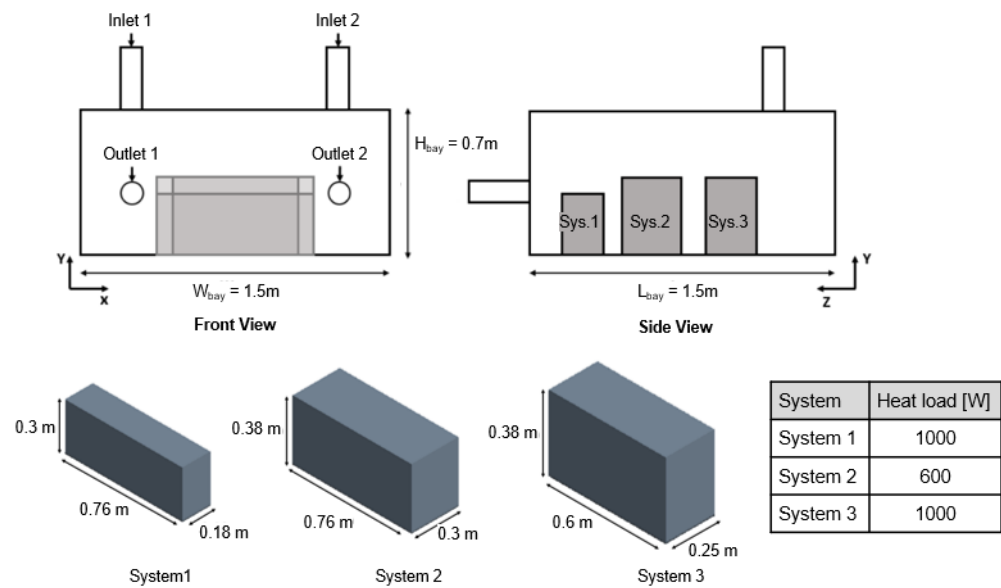


Figure 3. Simplified cockpit underfloor equipment bay with dimensions and air-inlet and outlet locations (Sys1, Sys2, and Sys3 refer to System 1, System 2, and System 3).

This configuration considers a hot day scenario with a ground-level ambient temperature of 55 °C (at 1 atm), which typically represents one of the most critical scenarios for aircraft thermal analysis. Due to the cockpit pressurization and controlled temperature, the top wall of the equipment bay, which is the cockpit floor, is assumed to be at 30 °C, whereas the underfloor equipment bay bottom wall is hotter at 55 °C. This configuration creates an unstable temperature gradient that requires modeling the buoyancy effects. All the other walls of the equipment bay are at 55 °C except the equipment bay left wall, which is assumed adiabatic. This wall represents the interface between the cockpit underfloor and the cabin underfloor equipment bay; its temperature depends on the thermal environment of the cabin underfloor bay, which is not considered in this study. According to the DO-160 standard [17–20], the systems have a temperature limit of 70 °C, which requires a mass flow rate of 0.035 kg/s-kW. Hence, to meet these standards, the total cooling mass flow rate is assumed at 0.0382 kg/s. The temperature of the inlet cooling air is assumed at 30 °C, and the outlet split ratio is 0.5, which means that outlets 1 and 2 extract the same mass flow. The boundary conditions are summarized in Table 1.

Table 1. Boundary conditions for the cockpit underfloor equipment bay (Configuration 1).

Entity	Boundary Condition	Physics Value
Inlet 1 and Inlet 2	Mass Flow Inlet	0.0191 kg/s at 30 °C
Outlet 1 and Outlet 2	Pressure Outlet	Split Ratio 0.5
Bay Left Wall	Adiabatic	-
Bay Right Wall	Constant Temperature	55 °C
Bay Top Wal	Constant Temperature	30 °C
Bay Bottom Wall	Constant Temperature	55 °C
Bay Front Wall	Constant Temperature	55 °C
Bay Back Wall	Constant Temperature	55 °C

The CFD model has the following characteristics:

- Ideal and incompressible gas model.
- Segregated flow and energy solvers with second-order convection schemes that use steady-state Reynolds Average Navier-Stokes equations (RANS) were selected because segregated solvers offered better convergence and numerical stability.

- To model the turbulence effects of the flow, the authors selected the $k-\omega$ SST turbulent model with all y^+ wall treatment based on benchmark studies conducted by Yuce and Pulat [21].
- Buoyancy is modeled using the Boussinesq approximation [22].
- Radiation is modeled using the S2S model of Star-CCM+, which is based on enclosure theory [23,24] and uses view factors to compute the radiative heat exchange.
- A mix of polyhedral and boundary layer meshes of 600 000 elements in total based on a grid independency study [25] (Figure 4).

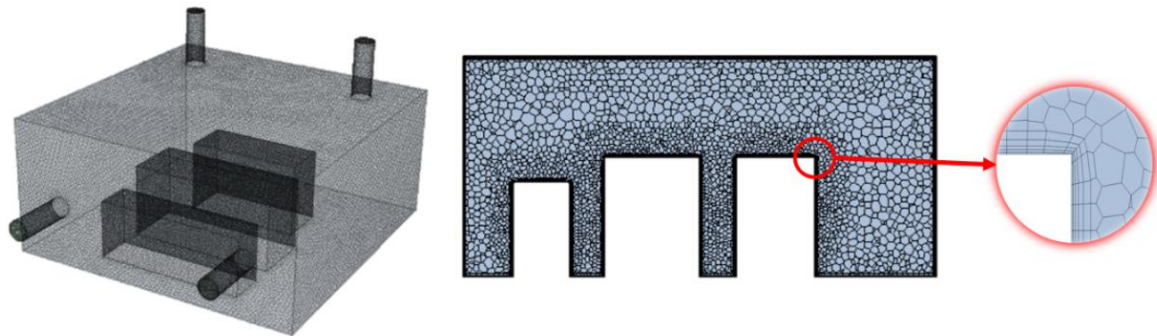


Figure 4. Mesh used in the CFD model for configuration 1.

2.2. Description of the Underfloor Equipment Bay (Configuration 2)

This second configuration deals with the cabin underfloor equipment bay, similar to the Bombardier Global 5000 (Figure 5). This configuration consists of two rows of eight systems located in a pressurized environment connected to the cockpit underfloor, the passenger cabin, and the belly fairing. In this CFD study, the authors investigate the effects of system distance gaps and ventilation flow rate on the system radiation magnitude.

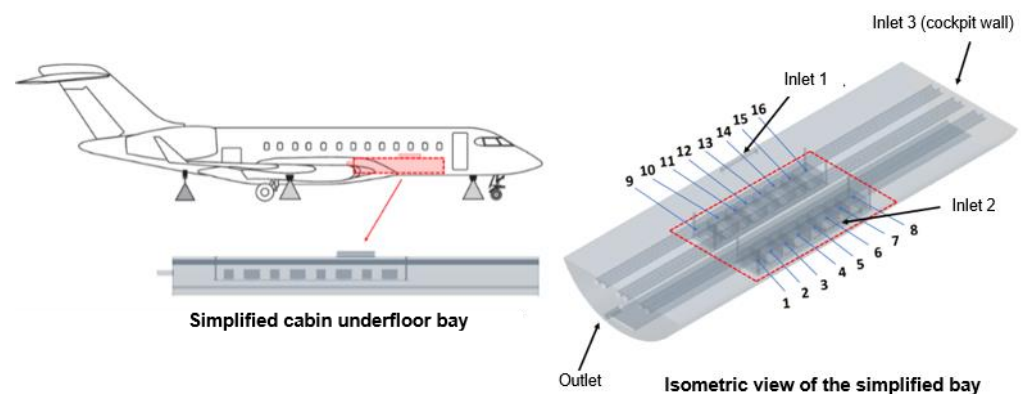


Figure 5. Cabin underfloor equipment bay in a business jet and derived simplified bay model with 16 cubic-shaped systems (Configuration 2).

In such an aircraft configuration, typically, the environmental control system (ECS) ventilates the air to the cabin underfloor equipment bay. The avionics exhaust system ensures the ventilation of the bay. The air enters the bay from the forward cabin exhaust. This air is then sucked through twin ducts via an avionics exhaust fan to the forward outflow valve [18]. To generalize the bay configuration, the authors replaced the exhaust ducts by a single-outlet exhaust fan. It is assumed that flow also enters the equipment bay via cockpit exhaust in addition to the passenger cabin exhaust. The total airflow provided to the equipment bay represents 50% of the ventilation flow extracted from the passenger cabin. The remaining 50% of the ventilation is recirculated to the passenger cabin.

The bay sizes are derived from a sketch available in the pilot training guide of the aircraft [19]. Figure 6 shows the generalized bay configuration.

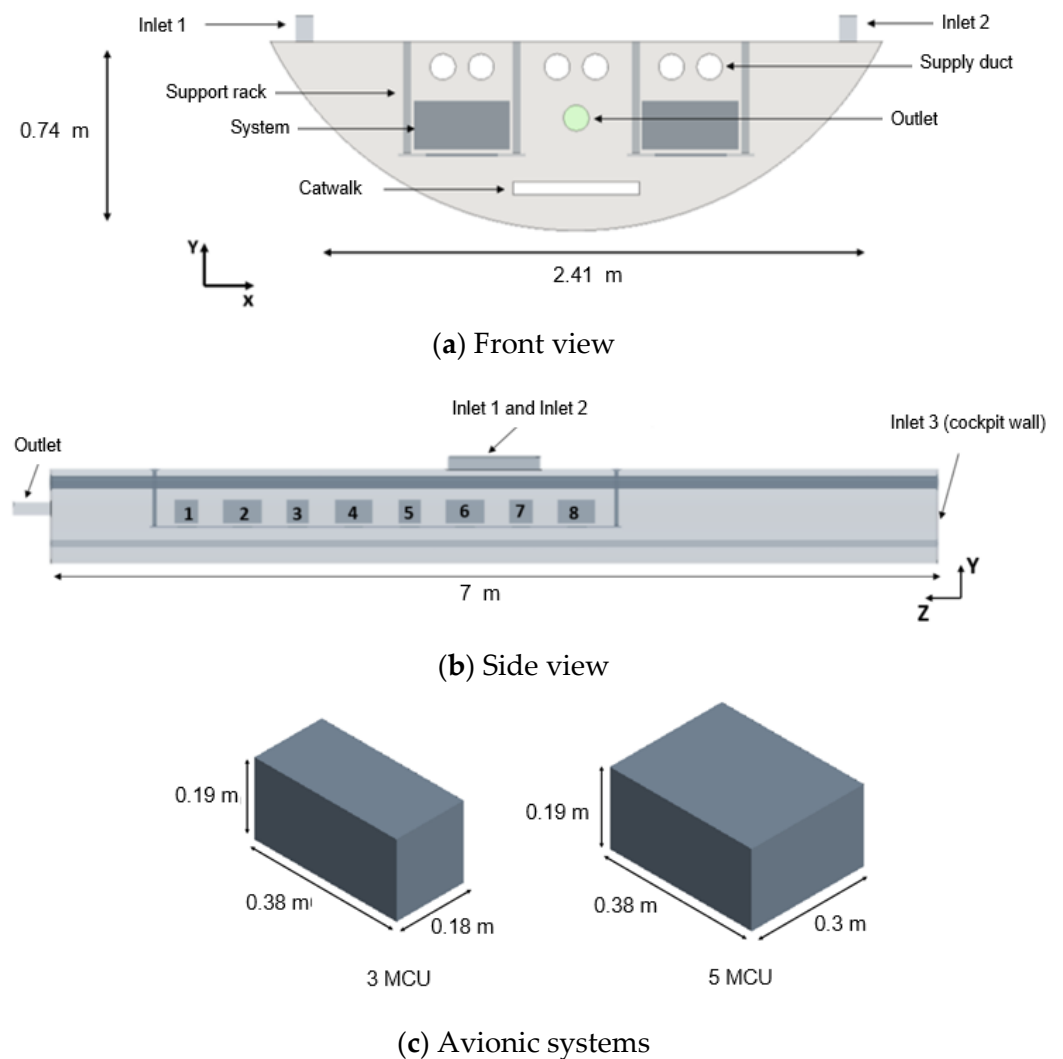


Figure 6. Geometrical description of the cabin underfloor equipment bay (Configuration 2).

This equipment bay consists of 16 systems, which are of the types 3 MCU and 5 MCU, according to avionics packaging standards, as depicted in Figure 6c. They dissipate 300 W, and 500 W heat loads, respectively, for this case study, similar to the assumptions made in [13]. The heat load dissipated by each avionic system is applied as a uniform heat source. The 3 MCU and 5 MCU systems are placed alternately, as shown in Figure 6b.

As per MIL-STD-1472G standard [20], for ease of maintenance, the minimum gap between avionics systems in equipment bays must be more than 0.045 m. The CFD study considers three different gap widths to evaluate the influence of the system gap on their radiative heat exchange. The smallest gap is 0.05 m, the minimum distance to satisfy certification constraints. The two other gap widths are 0.1 m and 0.2 m, representing more considerable distances between the equipment when connection and wires require more space between the systems. The CFD study also considers three different ventilation flow rates representing different operating conditions of the ECS. The flow repartition is then derived from the ECS supply flow and assumed to be 22% for the cockpit and 78% for the passenger cabin. Table 2 shows the parametric study conducted for the cabin underfloor equipment bay.

Table 2. Parametric study for the cabin underfloor equipment bay (Configuration 2).

Case	Mass Flow Rate (kg/s)				Gap (m)
	Inlet 1 (39%)	Inlet 2 (39%)	Inlet 3 (22%)	Total	
1	0.0266	0.0266	0.0150	0.0682	0.05
2	0.0266	0.0266	0.0150	0.0682	0.1
3	0.0266	0.0266	0.0150	0.0682	0.2
4	0.0532	0.0532	0.0300	0.1363	0.05
5	0.0532	0.0532	0.0300	0.1363	0.1
6	0.0532	0.0532	0.0300	0.1363	0.2
7	0.1063	0.1063	0.0600	0.2726	0.05
8	0.1063	0.1063	0.0600	0.2726	0.1
9	0.1063	0.1063	0.0600	0.2726	0.2

This study considers the ambient air temperature of 55 °C (at 1 atm). The top wall is at 30 °C, and the other bay walls are at 55 °C. Other objects inside the bay, such as the catwalk and the supporting rack, are assumed adiabatic to make this study as generic as possible. This equipment bay configuration has three inlets and one outlet, and the cooling air temperature is 30 °C. Table 3 summarizes the boundary conditions.

Table 3. Boundary conditions for the CFD study of the cabin underfloor equipment bay (Configuration 2).

Entity	Boundary Condition	Physics Value
Aft Cabin Wall	Constant Temperature	55 °C
Bay Bottom Wall	Constant Temperature	55 °C
Catwalk	Adiabatic	-
Inlet 1	Mass Flow Inlet	Case dependent
Inlet 2	Mass Flow Inlet	Case dependent
Inlet 3	Mass Flow Inlet	Case dependent
Outlet	Pressure Outlet	Split Ratio 1
Supply Duct	Constant Temperature	30 °C
Supporting Rack	Adiabatic	-
Bay Top Wall	Constant Temperature	30 °C

The CFD model has the following characteristics:

- Ideal and incompressible gas model.
- Segregated flow and energy solvers with second-order convection schemes that use steady-state Reynolds Average Navier-Stokes equations (RANS) were selected because segregated solvers offered better convergence and numerical stability.
- To model the turbulence effects of the flow, the authors selected the k- ω SST turbulent model with all y+ wall treatment based on benchmark studies conducted by Yuce and Pulat [21].
- Buoyancy is modeled using the Boussinesq approximation [22].
- Radiation is modeled using the S2S model of Star-CCM+, which is based on enclosure theory [23,24] and uses view factors to compute the radiative heat exchange.
- A mix of polyhedral and prism layer meshes of 3 800 000 elements in total based on a grid independency study [25] (Figure 7).

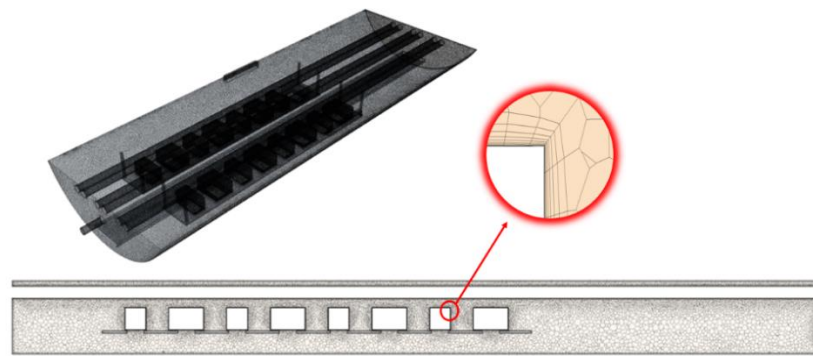


Figure 7. Mesh of the CFD model of configuration 2.

3. Results and Discussions

3.1. Effects of Radiation Heat Transfer on System Thermal Environment

Configuration 1 has been used to highlight the effects of radiation heat transfer on the overall system thermal environment. Table 4 shows the results obtained for the surface averaged temperatures of the systems with and without radiation. It also gives the fraction of radiation in the total system heat flux. Figure 8 shows the CFD results obtained with and without considering radiation.

Table 4. System surface-averaged temperature and radiative heat flux for Configuration 1.

System	Without Radiation	With Radiation	
	Temperature (°C)	Temperature (°C)	Radiative Heat Flux Ratio
System 1	125.9	83.6	0.49
System 2	135.9	90.0	0.47
System 3	133.2	81.9	0.50

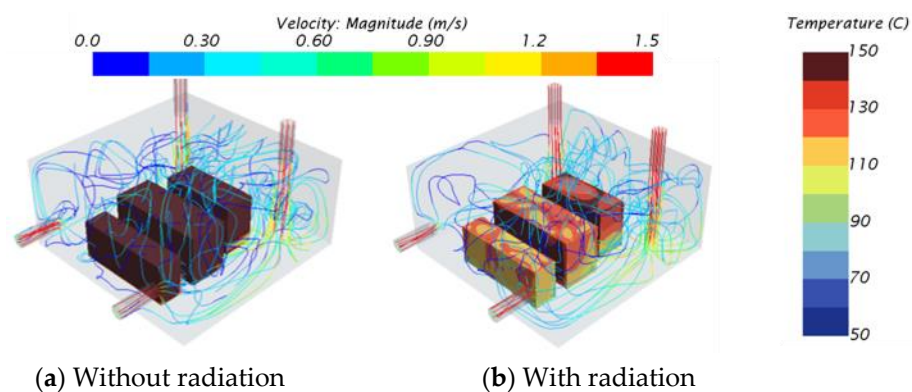


Figure 8. System surface temperature contours and velocity streamlines for the cockpit underfloor equipment bay (Configuration 1).

The results show that the radiative heat transfer brings down the temperature of the systems by 50% to 60%. Indeed, radiative heat exchanges with the adjacent systems and the bay walls allow the considered systems to exchange additional thermal energy. Moreover, the contribution of radiation represents 50% of the total heat flux dissipated by the systems.

Figure 9 shows the air temperature surrounding the systems without and with radiation considered in the CFD simulation. When neglecting radiation, the boundary layer temperatures of the systems are hotter than when considering radiation. This means the systems dissipate more heat to their surrounding air when no radiation happens. In other words, radiation heat flux weakens the boundary layer. Figure 10 shows that radiation inside an equipment bay also impacts the velocity field. Because the systems dissipate more heat in their surrounding air, the plume effects are more substantial without radiation.

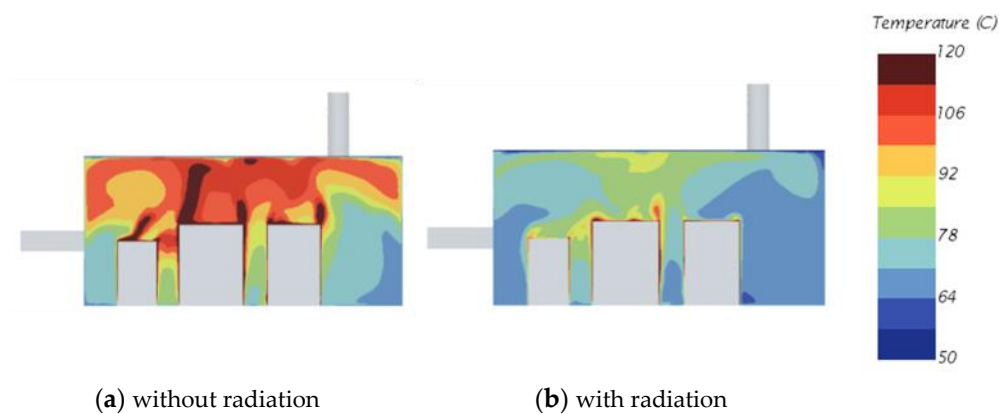


Figure 9. Cross-sectional view (centered on Outlet 1) of the air temperature for the cockpit underfloor equipment bay (Configuration 1).

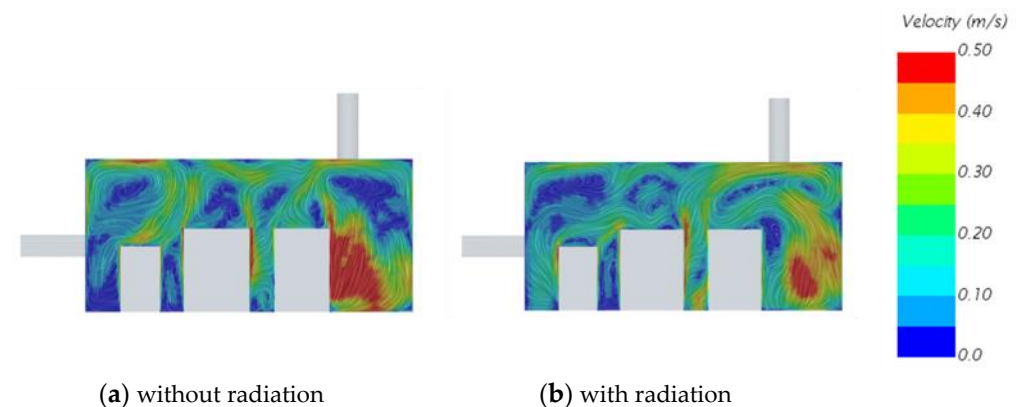


Figure 10. Cross-sectional view (Centered on Outlet 1) of the velocity magnitude contour for the cockpit underfloor equipment bay (Configuration 1).

Overall, this study reveals that radiation significantly impacts equipment surface temperature and the overall thermal environment of an equipment bay. Radiation consideration cannot always be neglected when studying the thermal management of aircraft equipment bays.

3.2. Effects of Gap Distance between Adjacent Systems and Ventilation Flow Rate on Radiation Magnitude

The underfloor equipment bay studied in configuration 2 allows the investigation of the impact of the gap distance between adjacent systems and the ventilation flow rate on the radiation magnitude. As the geometry of the underfloor equipment bay is symmetric, the following discussions will focus only on one side of the bay, which contains systems 1 to 8, and the temperature and velocity contour results will be only shown for the area defined by the red rectangular box in Figure 11.

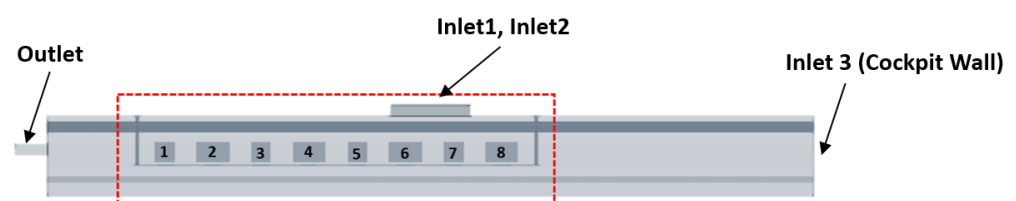


Figure 11. Side view of the underfloor equipment bay (Configuration 2).

Figure 12 shows the CFD results for the velocity streamlines generated from the inlets. The mainstream inlet flows influence the systems thermal behavior close to the inlets. This

allows organizing the systems into three groups according to their relative location with the inlets and outlets of the equipment bay.

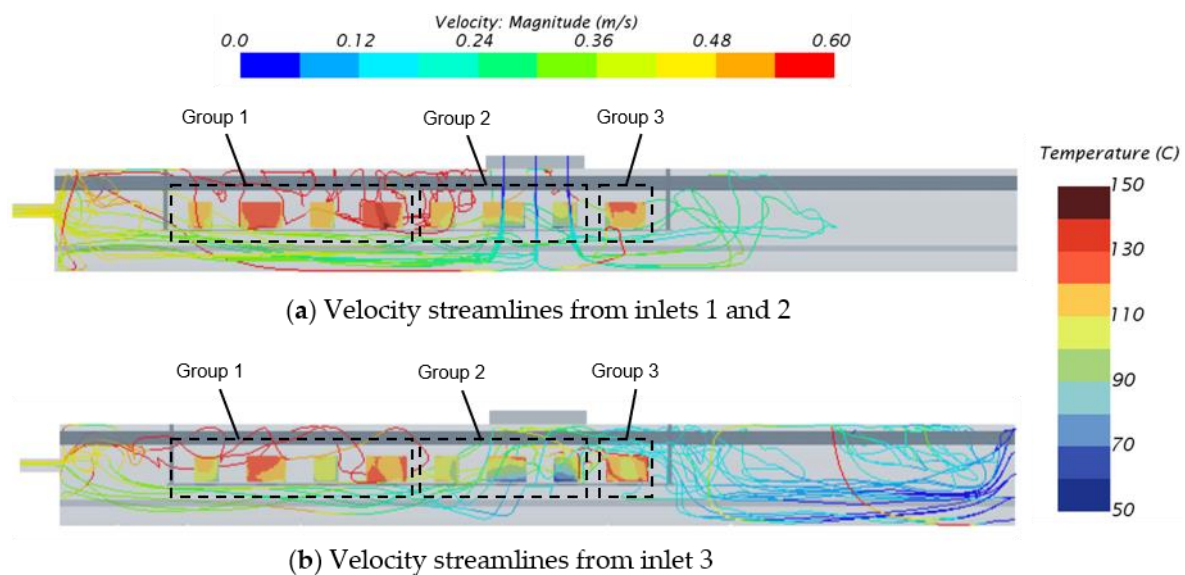


Figure 12. Velocity streamlines from inlets 1, 2, and 3 for the underfloor equipment bay (Configuration 2).

Group 1 contains systems 1, 2, 3 and 4, located between the outlet and inlets 1 and 2 (cabin exhaust). Group 2 includes systems 5, 6 and 7 in front of inlets 1 and 2. Finally, Group 3 contains system 8 facing inlet 3 (cockpit exhaust).

To assess the proportion of radiation in the overall system heat transfer, the radiative and the total system heat fluxes are derived from the CFD results and used to calculate the radiative heat flux ratio. Figure 13 shows the evolution of this ratio averaged per group with the system distance.

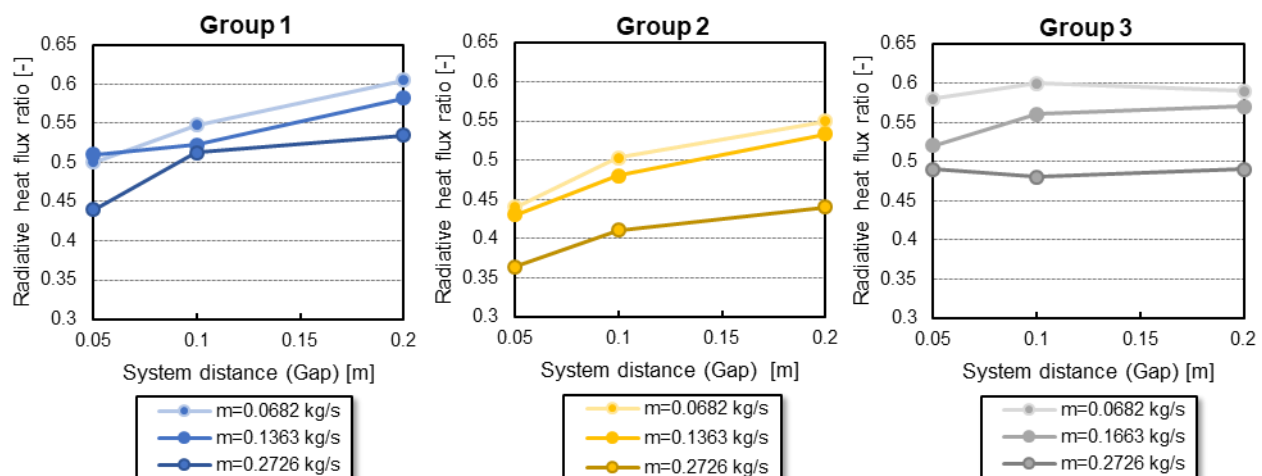


Figure 13. Evolution of the radiative heat flux ratio with system gap distance for different inlet mass flow rates (Configuration 2).

For groups 1 and 2, the radiative heat flux ratio increases with the gap distance between the systems for all the mass flow rate values. Figure 14 shows the velocity contour for cases 1, 2, and 3 for the three studied gap distances with the smallest flow rate value. Here the CFD results show that the velocity magnitude in the gap area between the systems increases with the gap width. This also means that a small gap between the systems leads to higher velocity magnitude and, therefore, stronger convective than radiative heat exchange.

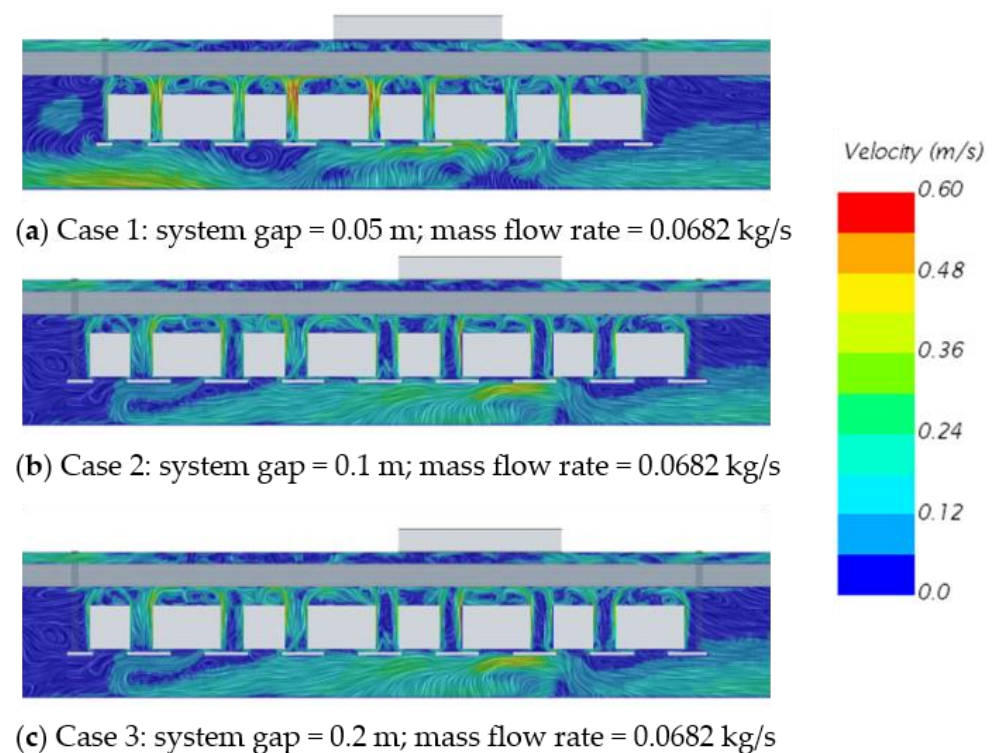


Figure 14. Velocity contour for Cases 1, 2, and 3 of the underfloor equipment bay (Configuration 2) for increasing gap distances and a constant mass flow rate.

For group 3, the radiative heat flux ratio stays almost constant with the gap width variation between the system. The radiative heat flux ratio is less sensitive to the gap width than the other groups. Since only one system is in the group, its interaction with the other system is less critical as it has only one side facing another system. Indeed, the flow coming from the cockpit exhaust reaches the system in the same way, independent of the gap distance. Thus, the convective heat exchange is always of the same order of magnitude, which explains why the radiative heat exchange stays almost constant.

The same observations are valid for higher mass flow rates represented by cases 4 to 9 (See Figures A1 and A2, and Table A1 in Appendix A).

Figure 15 shows the radiative heat flux ratio as a function of the inlet mass flow for the three groups of systems.

For groups 1 and 2, the radiative heat flux ratio decreases with the mass flow rate for the three different system distances. Increasing mass flow rate leads to increased convective heat exchange between the systems and their environment; this increased convective heat exchange becomes more important than radiation. Figure 16 shows the velocity contours for cases 2, 5, and 8, which have the same system distance but different mass flow rates. The velocity magnitude in the gap between the systems increases with the distance, which confirms that convective effects gain in intensity with the distance between the systems.

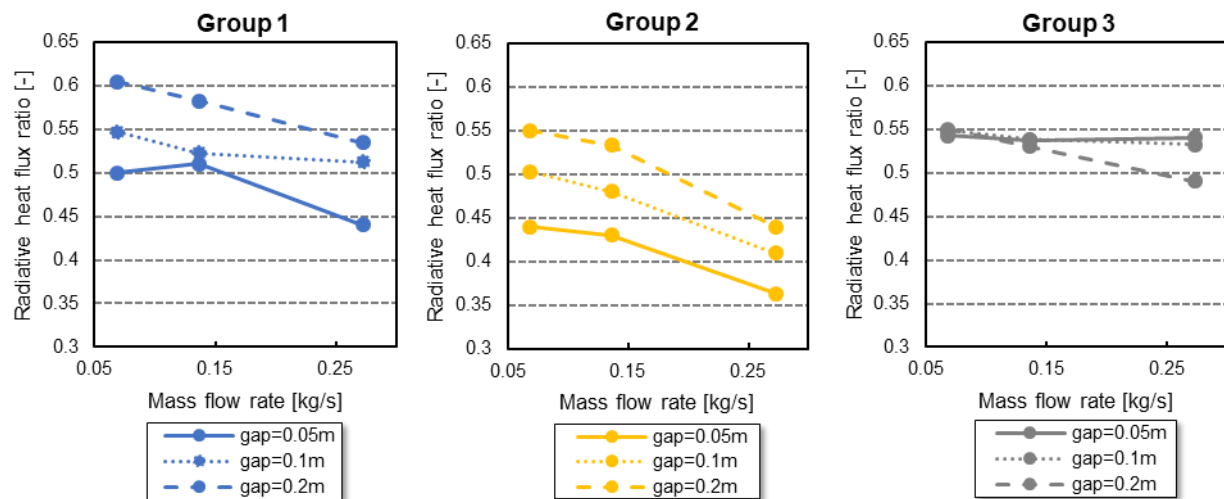


Figure 15. Evolution of radiative heat flux ratio with inlet mass flow rate for different system gap distances (Configuration 2).

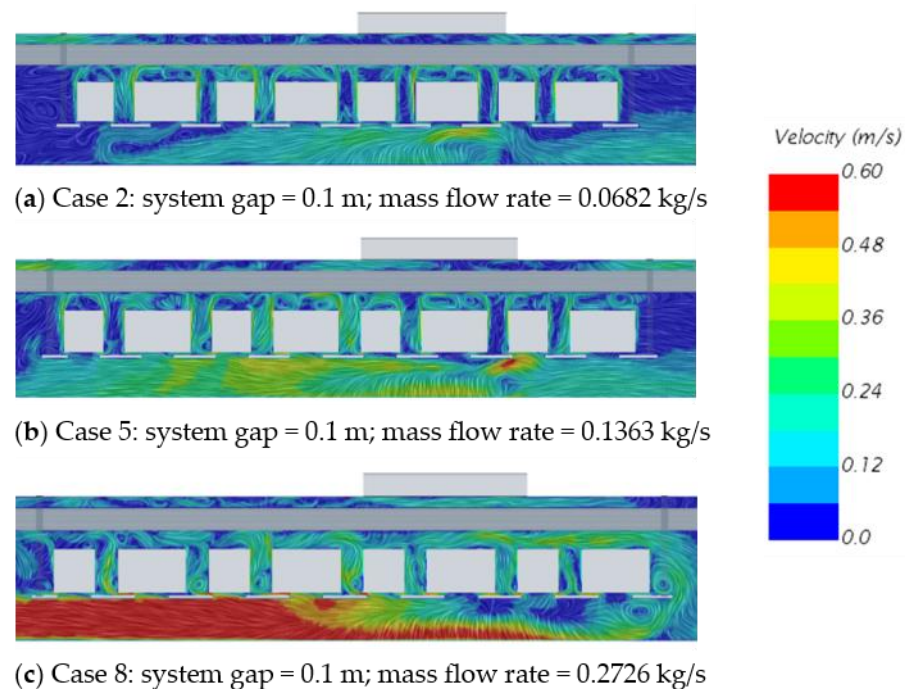


Figure 16. Velocity contours for Cases 2, 5, and 8 of the underfloor equipment bay (Configuration 2) for increasing mass flow rates and a constant system gap.

For group 3, the radiative heat flux ratio stays constant while the mass flow rate increases, except for the lowest value of the inlet flow rate (Figure 15). The combination of low flow speed and large system gap (Figure 14c, Case 3) allows more air to fill the gap between systems 7 and 8, consequently increasing the convective effects at the cost of the radiative ones.

The previous paragraphs highlight the scenarios where the radiative heat exchanges prevail. In this last paragraph, the discussions will focus on the thermal environment of the three cases with the highest radiative heat flux ratio. Figure 17 shows the temperature contour for cases 3, 6, and 9. These cases have all the maximum gap distance considered in this study, which shows that the gap distance plays a major role in the radiation exchange. However, the temperature contours show that the mass flow rate has a non-negligible effect on the system's thermal environment, even though convective effects are less dominant

than radiation. When the mass flow rate increases, the inlet flow reaches more systems downstream (Group 2). However, the four systems from Group 1 (Left part of the bay in Figure 17), which have the highest radiative heat flux ratio, have the hottest environment for all inlet flow rate values.

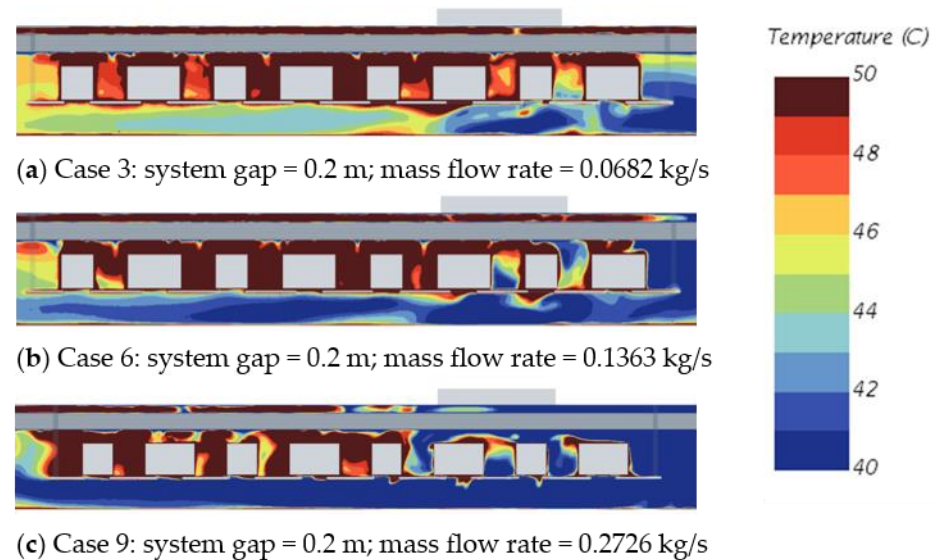


Figure 17. Air temperature contour for Cases 3, 6, and 9 of the underfloor equipment bay (Configuration 2) when radiative effects are dominating.

4. Conclusions and Axes for Future Work

This paper investigates the influence of radiation on the overall system heat dissipation in two representative underfloor equipment bays of commercial and business aircraft. The authors use CFD simulations to demonstrate that heat radiation might significantly impact the equipment's thermal environment.

A first case study dealing with a simplified cockpit underfloor equipment bay demonstrates that radiation exchange represents 50% of the overall heat flux dissipated by a system in its environment. Thus, radiation must be considered when studying an avionics thermal environment.

Then, a parametric study conducted in a generic but representative cabin underfloor equipment bay investigates the effects of ventilation flow rates and gap distances between adjacent systems on radiation magnitudes. The first outcome of this study is that the inlet mainstream flow affects the extent of radiation effects. Thus, the systems are grouped based on their relative location with regard to the inlet flow sources. Secondly, the authors analyze the sensitivity of system radiation heat flux with the gap distance between adjacent systems. Increasing the distance between two adjacent systems leads to higher radiative heat flux dissipation. On the other hand, increasing the inlet mass flow rate increases the convective heat exchange, thus reducing the radiative heat flux dissipated by the systems.

In summary, this paper's results suggest that the radiative effects must be considered when:

- The gap distance between the systems is larger than 0.1 m;
- The flow rate between two systems is not strong enough to have high convective heat exchanges;
- The systems of interest are hidden by other systems from the ventilation sources;
- The systems of interest have significant internal heat dissipation.

Concluding, the results of the paper are important for aircraft manufacturers and system designers to focus on the type and depth of thermal analysis in early design phases.

Within this paper, the authors focus on a qualitative approach to assess the effects of the ventilation flow rate of an equipment bay and the gap distance between the systems

on the radiation magnitude. Future work will focus on a quantitative assessment, which requires more extensive and detailed radiation calculations of radiation impacts on cooling system requirements of aircraft equipment bays. It is also expected that the contribution of the radiative cooling will decrease with the avionics box's heat dissipation if the avionics box is internally ventilated. In this paper, the avionic boxes considered were sealed and cooled solely by their surfaces. Therefore, future work should address more extensive parametric studies dealing with system heat loads and wall and inlet temperatures to cover more aircraft operating conditions and other types of systems (e.g., different types of avionics boxes, batteries, hot air ducts, or motors) relevant for future aircraft featuring significant thermal challenges.

This extensive study, combined with the presented paper's results, will allow for the derivation analytical correlations suitable for aircraft conceptual design, in particular, to enhance the previously developed thermal risk analysis (TRA). Those correlations will also indicate when it is necessary to include radiation in the cooling model for more advanced thermal analyses. Thus, with representative and easily usable correlations, conceptual aircraft designers will benefit from the guidelines and results presented in this paper to consider radiation when optimizing aircraft thermal management.

Overall, this paper's results will contribute to enhance conceptual design methods, such as the TRA, and help optimizing thermal analysis and management strategies for future aircraft.

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Conflicts of Interest: The authors declare no conflict of interest. Bombardier, as one of the funders, advised in the study's design and the interpretation of data; they also reviewed the results before publication.

Appendix A

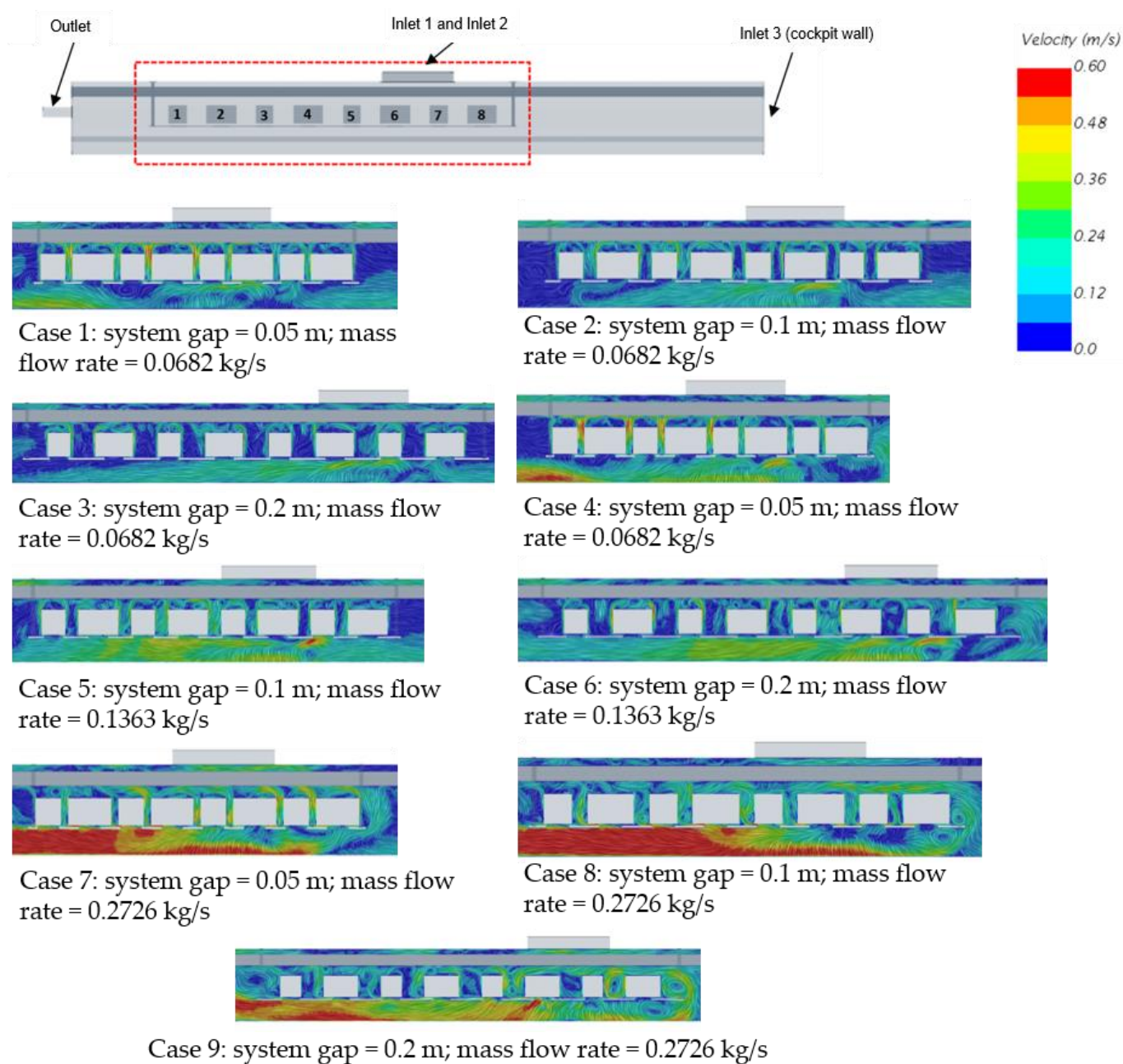


Figure A1. Velocity magnitude contour for all studied cases of Configuration 2.

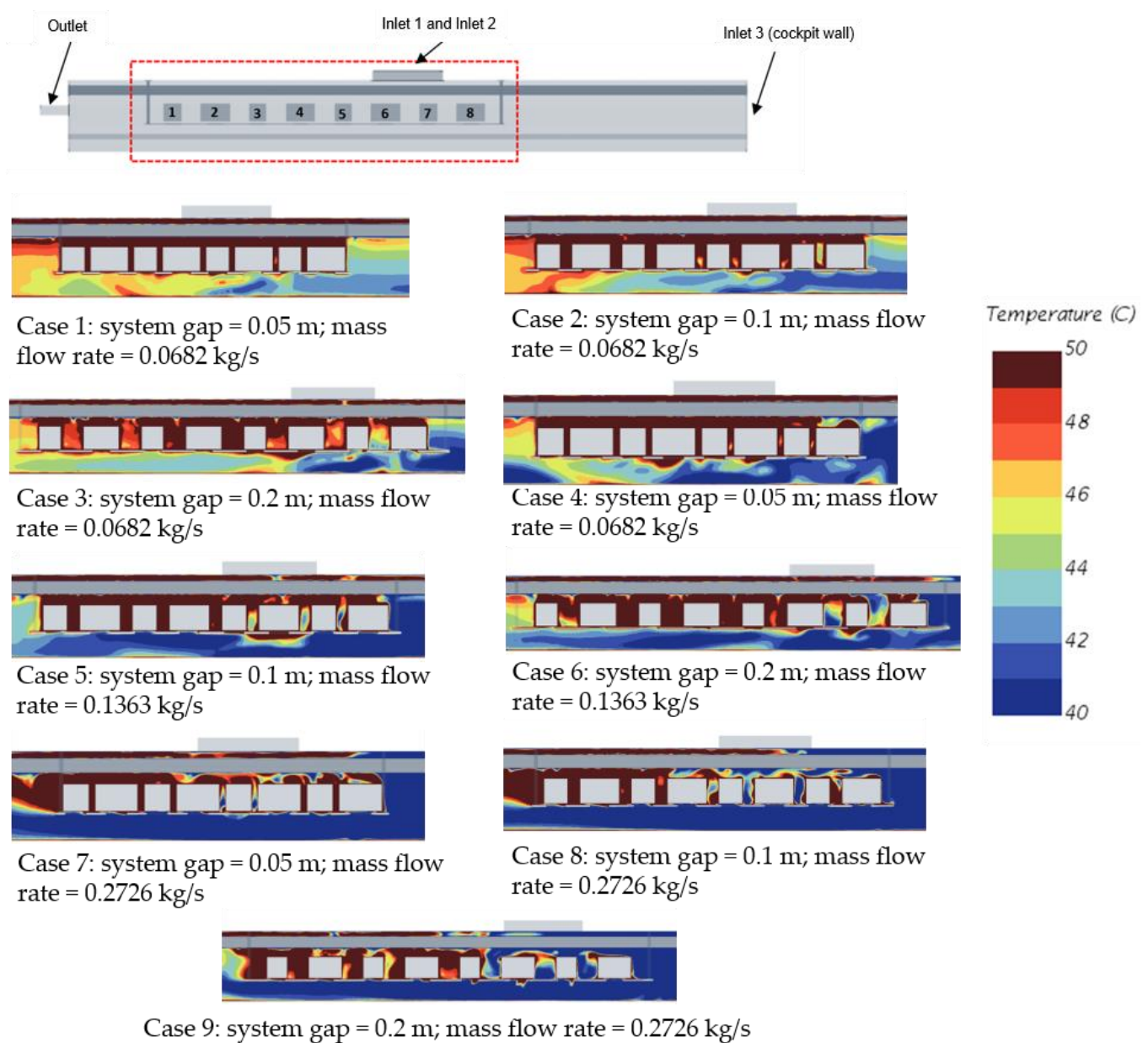


Figure A2. System temperature contour for all studied cases of Configuration 2.

Table A1. System radiative heat fluxes for all studied cases of Configuration 2.

Total Heat Flux [W/m ²]			Radiative Heat Flux [W/m ²]								
System	Type	Heat load/Area	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
1	3 MCU	858.1	450.8	487.2	510.8	435.2	460.1	497.1	407.2	441.3	469.4
2	5 MCU	1028.0	534.7	588.0	643.4	525.3	558.8	614.7	503.5	538.2	560.4
3	3 MCU	858.1	370.5	428.9	484.9	356.2	408.4	475.3	317.9	374.9	430.6
4	5 MCU	1028.0	529.7	563.6	636.4	509.9	540.1	612.2	446.3	491.8	556.0
5	3 MCU	858.1	357.7	416.6	464.4	350.4	392.4	462.1	276.5	325.0	388.7
6	5 MCU	1028.0	505.0	576.3	611.7	490.9	535.1	564.6	418.3	450.1	462.1
7	3 MCU	858.1	352.3	391.6	437.7	341.6	393.8	436.0	305.5	353.9	357.1
8	5 MCU	1028.0	599.1	617.5	610.8	538.6	575.5	583.9	506.0	494.5	502.3
9	3 MCU	858.1	454.9	478.0	505.0	439.7	451.7	484.4	403.0	444.8	473.2
10	5 MCU	1028.0	535.5	583.7	636.7	521.0	552.8	613.2	488.9	526.1	576.3
11	3 MCU	858.1	369.3	427.5	477.1	357.3	420.9	471.2	337.9	377.6	439.7
12	5 MCU	1028.0	531.5	579.1	626.8	526.2	542.7	608.9	426.1	509.0	545.0
13	3 MCU	858.1	367.3	420.5	477.1	341.6	380.4	448.8	272.2	321.8	401.5
14	5 MCU	1028.0	515.1	545.3	615.8	504.1	510.5	565.5	416.1	429.7	455.1
15	3 MCU	858.1	352.9	392.2	441.5	329.6	374.9	428.6	303.5	333.2	383.1
16	5 MCU	1028.0	599.8	595.4	609.2	533.3	576.7	588.2	493.6	483.0	521.5

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