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Aircraft Level Thermal Management Analysis for Early Design Stages of Future Aircraft: Integration of Systems and Compartments into an Interacting Generic Approach †

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Abstract: For future commercial aircraft having hybrid electric drivetrains, the impact of electrical power generation and distribution on heat production and required heat rejection is of a larger magnitude than for conventional aircraft. The thermal management system (TMS) to control component and compartment temperatures may require dedicated solutions. The impact of TMS on top-level aircraft requirements (TLARs), e.g., weight and drag penalties, should become clear in the early stages of design for integration in the configuration. To assess this impact, a generic approach is presented to support aircraft level thermal management analysis and design based on global aircraft parameters.

Keywords: (hybrid-)electric drivetrain; component efficiency; heat rejection; thermal management; compartment model; cooling loops; weight, drag and volume penalties

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1. Introduction

Societal demand for greener aircraft has matured into aviation visions for the future, e.g., Fly the Green Deal [1], and has sparked investigations into alternative (hybrid-)electric propulsion options for aircraft of various sizes. Research is speeding up to deliver viable future aircraft propulsion concepts by 2035 to meet the goals and objectives of the Green Deal. A severe bottleneck is the thermal management of those new megawatt-class electric or hybrid electric drivetrains. Despite relatively high electrical component efficiencies, the powers involved are huge and so are the amounts of heat produced at each conversion or component passage. The produced heat needs to be rejected by a well-designed thermal management system (TMS) respecting the operational temperature range of components under all the envisaged operational environmental temperature conditions. A recent overview of TMS investigations and approaches following the larger cooling demand due to increased electrification of aircraft and subsystems is given in [2]. A dynamic simulation including the use of nanoparticles in coolant is outlined in [3].

Recently, the IMOTHEP project (Investigation and Maturation Of Technologies for Hybrid Electric Propulsion) assessing viable hybrid electric propulsion options for commercial aircraft has ended. An overview of the activities and main results from the project is outlined in [4] and general project information can be found on the website [5]. IMOTHEP studied four different configurations: regional conservative aircraft (REG-con), regional radical aircraft (REG-rad), short-to-medium range conservative aircraft (SMR-con), and most recently a short-to-medium range radical aircraft (SMR-rad) [6]. In the following, the work performed within IMOTHEP is described on the analysis and design of TMS for commercial aircraft, focusing on SMR aircraft with turbo-electric propulsion, although the generic approach can be adjusted for other types of drivetrains as well.

2. Materials and Methods

For increased cooling requirements on new future aircraft employing high-power (hybrid-)electrical propulsion (HEP) drivetrains, a TMS simulation method has been developed for the investigation of a proposed TMS and its characteristics. Such an investigation takes place at the overall aircraft level in the early design stages of development and delivers cooling and/or heating needs as well as the design guidelines for the cooling loops. Since for new future aircraft types the required cooling power of the TMS has to be identified early in the design process in order to take the weight, volume, and drag penalties into account, a significant constraint placed on the methodology is to use as little specific aircraft information as possible while providing ample output on cooling needs. Following these constraints, a lumped thermal model is embraced. The method can be applied in the analysis as well as in the design mode. In the current set-up of the method, use is made of conventional cooling methodologies using ambient air, engine oil loops, hydraulic coolant loops, and even fuel as coolant, but for future extensions of the method, the application of two-phase pumped loops or more unconventional approaches such as cryogenic coolants or heat storage might be considered. The main question to be answered each time is the implication of the required cooling system on top-level aircraft requirements (TLARs), such as range, payload, cruise altitude, and propulsive power requirements.

The method has three interacting layers, shown in Figure 1. The main layer consists of the propulsion system. Details of the propulsion system differ for each specific type of (H)EP drivetrain. Transforming energy in propulsive power leads to losses in components of the drivetrain, e.g., in electric motors, power electronics, distribution buses, and generators. The analysis of the cooling requirements results from the state-of-the-art or future efficiencies of such components. The next layer is that of the cooling subsystems: in this case air, hydraulic coolant, engine oil, and fuel are selected as coolants. The components in the drivetrain are subjected to one or multiple of these coolants. Associated cooling loops may be composed of tubing, heat exchangers, pumps, reservoirs, and the like. The entire set of subsystems formed by the coolant loops including controllers forms the thermal management system, and the dimensioning of cooling loops is based on the cooling requirements. The final layer is the compartment model of the aircraft. As components of the drivetrain and of the cooling loops are located somewhere in the aircraft, component heat rejection and temperatures interact with the air in the various bays, pushing bay temperatures up. Aircraft compartments mutually exchange heat based on the existing temperature differences and also with the environment in case bays have exposed external skin. External heat sources are limited to solar irradiation.

The TMS simulation method has two modes of operation. Typically, an analysis is performed on a prescribed drivetrain and assumed cooling loops, and the analysis shows the resulting temperatures of components and compartments under various assumed environmental conditions such as cruise, hot day take-off under tropical sun, cold day startup without solar irradiation, etc. However, sometimes a design mode proves to be more useful. In design mode, additional cooling requirements can be assessed with or without already active cooling loops based on one of the selected available coolants. Such an approach helps to determine the required amounts of coolants to achieve a dedicated cooling objective and realistic boundaries of various types of cooling options can be assessed, e.g., by looking at the associated estimated heat exchangers weights and volumes.

Inputs to the aircraft level thermal simulator in its current shape are data files describing (a) general input like deviation from international standard atmosphere (ISA) temperature and lower heating value (LHV) of fuel used, (b) drivetrain component efficiencies, (c) trajectory of design or typical operational leg, (d) aircraft configuration-specific compartment volumes and areas. Some aspects are programmed hard in the simulator, such as the sequence of drivetrain components and associated power connections. Pondering options to make this part also more flexible for future applications, including potential failure case scenarios, is ongoing.

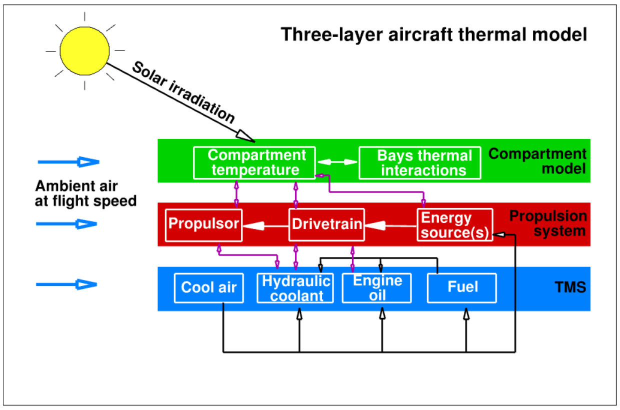
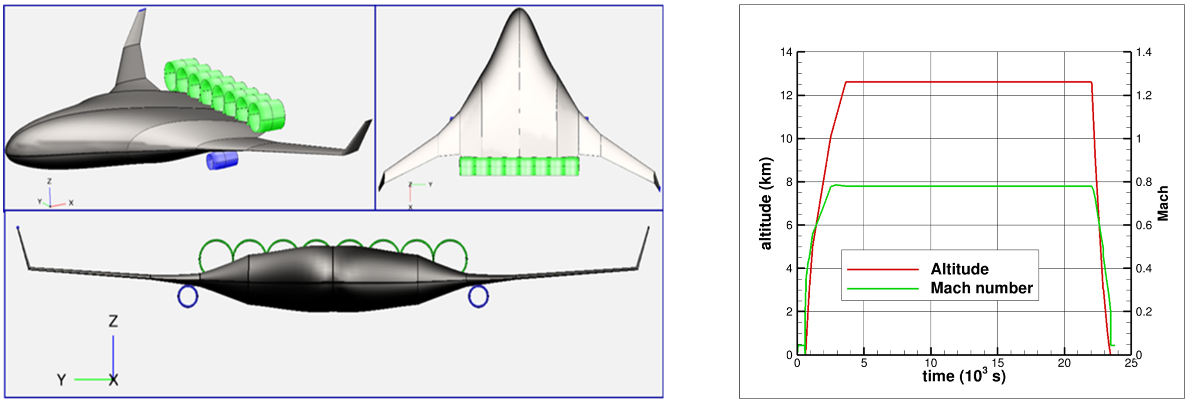


Figure 1. Schematic representation of three-layer aircraft thermal model. Interactions as shown are optional, depending on actual selected drivetrain and TMS characteristics.

For the compartment model, especially the thermal interaction between aircraft bays, a detailed investigation has been performed to assess the best way to select and place variables for accurate dynamic simulations within a lumped approach, see Appendix A.

3. Results

Aspects of method development and analysis results of a complete SMR-con turboelectric drivetrain including cooling loops are presented in [7,8]. The current results apply to the SMR-rad blended wing-body (BWB) configuration, with the drivetrain consisting of eight electric propulsion units (EPUs) each with an electric motor and inverter, four propulsion buses, four distribution buses, four rectifiers, four generators, and two turboshaft engines. The configuration and its 2750 nm design range flight profile are shown in Figure 2.

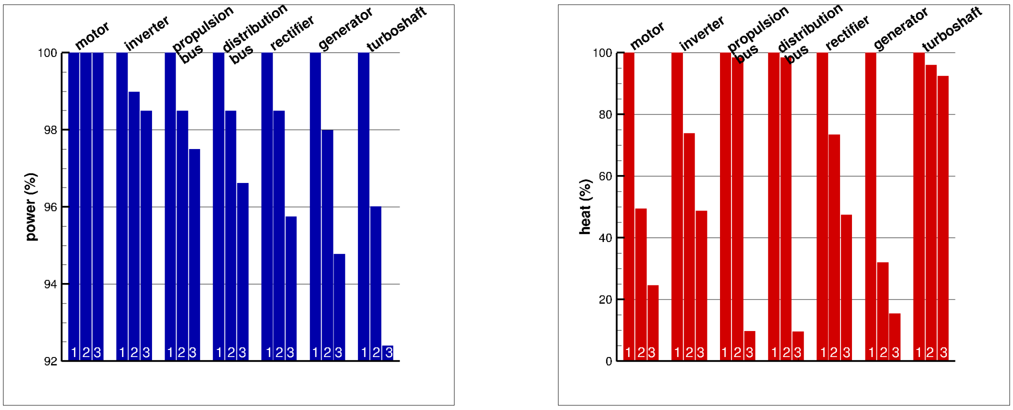


(**a**) (**b**)

Figure 2. (**a**) SMR radical configuration; (**b**) input design range flight profile.

An initial set of results comes from a straightforward analysis of the propulsion system. The impact of efficiency improvements for components in the drivetrain is shown in

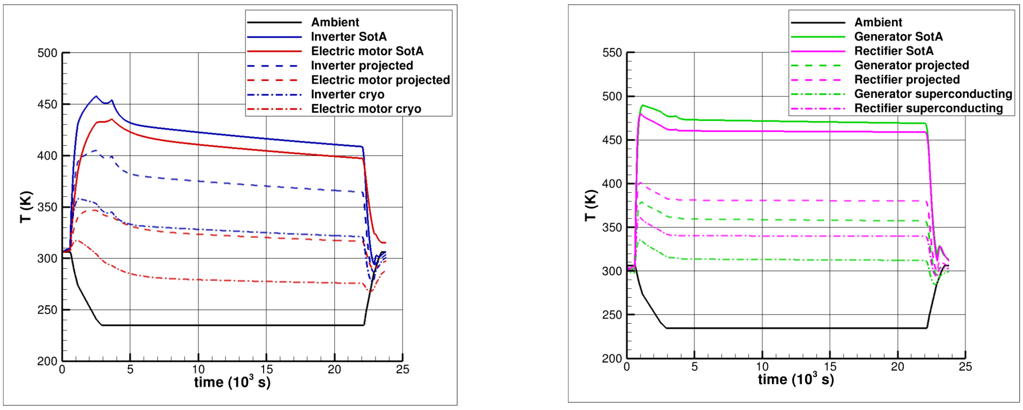
Figure 3, where for each component of the drivetrain the state-of-the-art (SotA) is set at 100%, and the reductions due to component improvements for the projected 2035 values as well as superconducting technology are shown in the next two bars per component. Efficiencies were reported earlier in [8]. For superconducting technology on top of 2035 projected values, the motors/generators are assumed to halve their losses, the power electronics have 2/3 of the losses, and especially the buses have only 10 percent of losses remaining. Apart from the turboshaft, the total heat generated by the drivetrain components at 1000 s in flight amounts to 1.75 MW, 1.14 MW, and 0.59 MW for the three cases, respectively.



(**a**) (**b**)

Figure 3. Impact of efficiency improvements from (1) state-of-the-art, (2) projected for 2035, to (3) cryo-cooling. (**a**) Component power reduction; (**b**) component heat generation reduction.

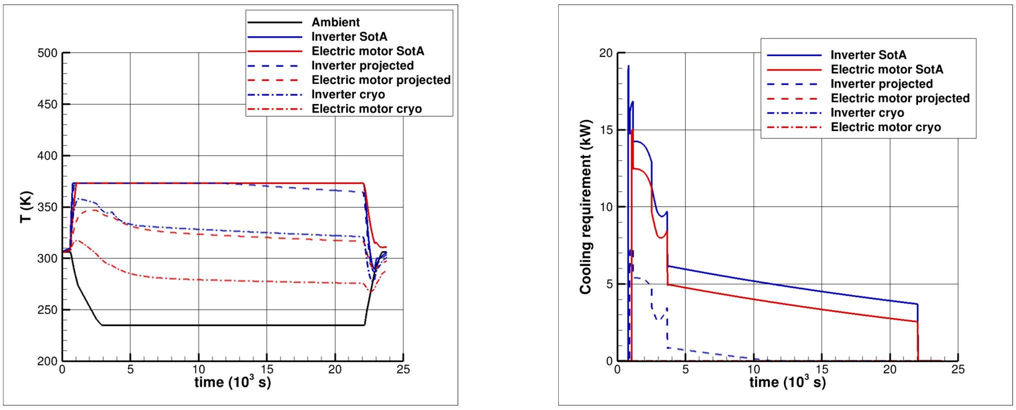
The TMS gives insight into the impact of the efficiency improvements on the temperature development of specific components over the design flight profile, see Figure 4 for a hot day condition when the international standard atmosphere temperature is 18 degrees higher than normal (ISA+18).



(**a**) (**b**)

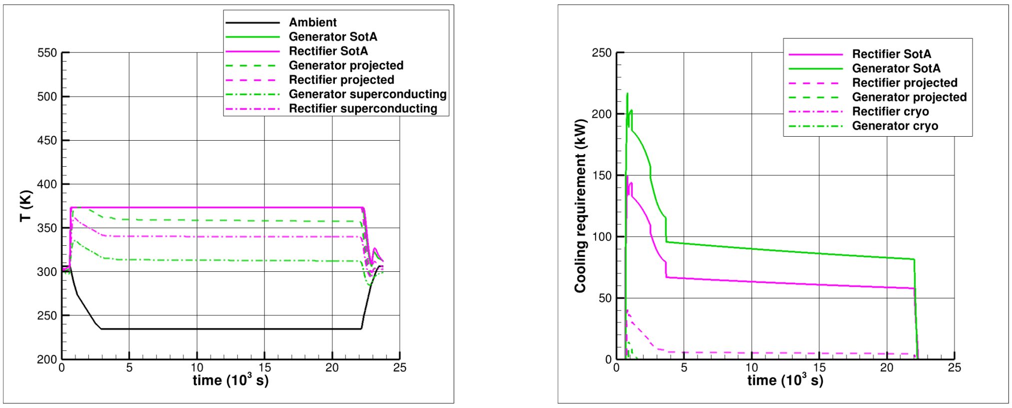
Figure 4. Efficiency improvement impact from (1) state-of-the-art, (2) projected for 2035, to (3) cryo-cooling, ISA+18. (**a**) Inverter and motor temperatures; (**b**) rectifier and generator temperatures.

It is assumed that the inverters and electric motors are air-cooled by the induced flow through the ducts of the EPUs, either from fan action, from forward flight, or from both. For the rectifiers and generators, it is assumed that a similar cooling loop arrangement has been used as for SMR-con [8], although the amounts of engine oil and coolant have been reduced. Taking the component's maximum temperatures into account, the temperature development and cooling requirement to achieve those temperatures are shown in Figure 5 for the inverters and electric motors, and in Figure 6 for the rectifiers and generators. It is shown that for the SotA-efficiencies, significant amounts of cooling are required over the entire flight duration, while for the projected efficiencies only a limited amount of cooling of predominantly the power electronics is needed, mainly during the high-loaded take-off and climb phase. The superconducting efficiencies automatically respect the component maximum temperatures under the current cooling loop assumptions based on higher efficiencies only; a cryo-reservoir that will bring down superconducting component temperatures further has not yet been implemented.



(**a**) (**b**)

Figure 5. Efficiency improvement impact from (1) state-of-the-art, (2) projected for 2035, to (3) cryo-cooling, ISA+18. (**a**) Inverter and motor temperatures with limitations; (**b**) inverter and motor cooling requirements.



(**a**) (**b**)

Figure 6. Efficiency improvement impact from (1) state-of-the-art, (2) projected for 2035, to (3) cryo-cooling, ISA+18. (**a**) Rectifier and generator temperatures with limitations; (**b**) rectifier and generator cooling requirements.

The compartment model relates the drivetrain and TMS to the ambient environment. How this is most elegantly performed is not a priori clear in a lumped approach and a separate small study has been performed to assess the placement of variables and model equations with the purpose of keeping the dynamic thermal behavior intact, see Appendix A.

An application of the compartment model to the aircraft cabin is elaborated for various extreme conditions. Assuming a hot worst-case scenario as ISA+35, at speed zero, i.e., standing on the platform, with maximum solar irradiation at noon on an equator airport position, and a cold worst-case scenario at ISA-60, at cruise speed and altitude without solar irradiation at a polar position, the cabin cooling requirements for both composite and metal skin are shown in Table 1.

Table 1. Cabin cooling requirements for SMR-rad to keep cabin temperature at 24 °C for fully occupied seating at extreme ambient conditions. Negative cooling requirements indicate heating!

ΔT-ISA (K)	Mach	Altitude (m)	Solar Irradiation	Skin Type	Cooling Requirement (kW)
−60	0.78	12,000	no	Metal	−239.8
	0.78	12,000	no	Composite	−174.7
35	0	0	yes	Metal	109.3
	0	0	yes	Composite	93.9

4. Discussion

The need for highly efficient drivetrain components is obvious. Higher efficiencies significantly reduce the amount of heat to be rejected. However, there is an important trade-off between the mass of high-efficiency components and the required cooling system. Very-high-efficiency lightweight components may require oil cooling and/or gear boxes, reducing the overall mass gains.

As the drivetrain is very similar to the SMR-con, apart from the number of EPUs, the analysis applies the same cooling loops, i.e., air cooling for the motor and inverter via the hub. However, the motor and inverter for SMR-rad are larger and deliver more power, but the ducts are also larger with higher mass flow. As shown for the SMR-rad [8], using fins on the hub increases the cooling potential and that would provide sufficient cooling for the inverter at projected 2035 efficiencies without further liquid cooling requirements. For the rectifier and generator, the same type of engine oil loop for the bearings and coolant loop for the electrical parts are used as for the SMR-con [8]. This includes fuel cooling of both coolant and engine oil. Figure 6 shows that with a little increase in the coolant flow, the generator and rectifier will also remain within temperature boundaries using 2035 efficiencies. Further optimization of cooling loops is, however, possible here, potentially alleviating the use of fuel as coolant.

The heating and cooling requirements for the cabin in extreme environmental conditions may look a bit surprising against the experience of a classical cabin. It should be noted in this respect that the cabin of a BWB shares a large area with the environment. Solar irradiation affects all of this area, while for a tube-shaped cabin, it would only affect part of the cabin area.

The cryogenic cooling of drivetrain components by its highly reduced heat losses due to superconducting properties would provide a major reduction in the overall power need of up to about 8 percent. The extra weight for insulated tubing and cryo-storage has not been included in the feedback loop, however, and data are missing to provide a good estimate for the associated weight penalty at this stage.

5. Conclusions

A methodology has been developed to assess overall aircraft thermal management and cooling for early design stages of (hybrid-)electric aircraft. The methodology is based on lumped nodal modeling and, although currently applied to turboelectric drivetrains, is generally applicable but may require specific adjustments for different types of drivetrains.

Depending on the availability of information, the inputs and outputs of the simulations can be enhanced to include one or more of the three interacting layers of the TMS. Minimum input is some form of the flight profile with Mach, altitude, and thrust defined over time.

Further development of the methodology is mainly wanted in the direction of verification and validation using well-defined experimental thermal data. Although an initial weight and volume penalty estimate has been derived for a TMS, the uncertainties involved in the data also call for more detailed weight, volume, and ram air data of realized, operational TMS configurations.

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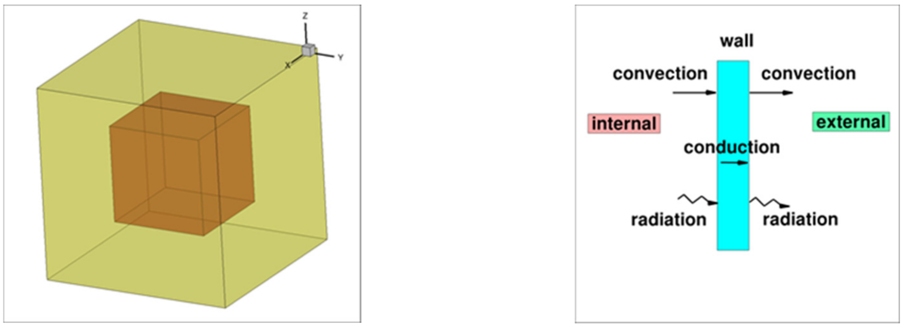
Appendix A

The selection and placement of variables to describe heat transfer through walls in dynamic simulations was varied within the lumped nodal approach. Correct dynamic simulation can be important as the available heat capacities of aircraft components may provide helpful temporary storage of heat. A test case of a hot component of 393 K inside a 1 m^3 bay surrounded by ambient air of 228 K was selected as shown in Figure A1a.

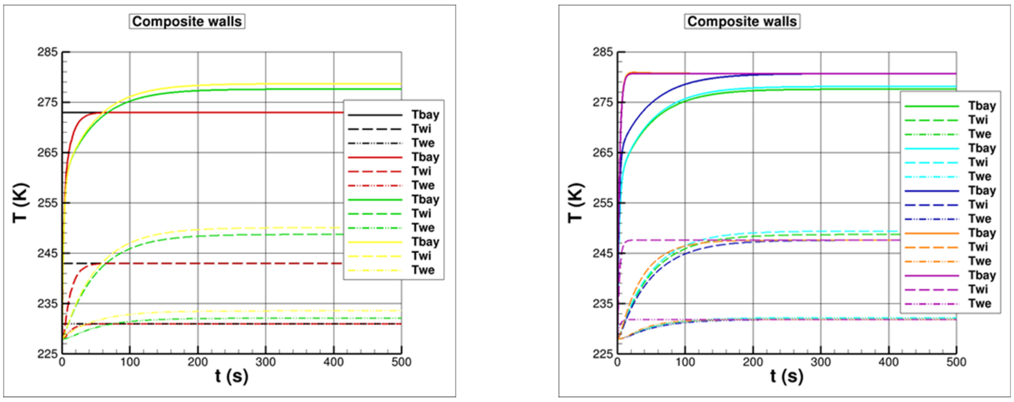


(**a**) (**b**)

Figure A1. Test case for dynamic heat transfer over a compartment wall. (**a**) Geometry of test case, showing a hot component inside a cubic bay surrounded by ambient air; (**b**) physical processes of heat transfer on both sides of the wall and through the wall.

Convection and radiation take place on both sides of the compartment wall, and conduction only through the wall, see Figure A1b. For heat transfer coefficients, several options are conceivable: (i) a full model requiring wall heat capacity and internal and external wall temperatures, and (ii) assumptions of various nature—mainly for radiation. The lumped model for this test case consisted of a node for the compartment air, a node for the inner wall, and a node for the exterior wall. Solar irradiation takes place only on the projected surface directed towards the sun, but as there is no distinction in nodes directed towards or shielded from the sun, the exterior temperature assumes one averaged value. Time-dependent equations were solved for the evolution of the nodal temperatures. The numerical method for the time integration is an explicit forward Euler method. It was observed that the stability of the time integration is sometimes compromised, which has for now been solved using smaller timesteps. Implicit time-integration methods like backward Euler could provide a more robust and time-step independent stability.

The following results are shown for a composite compartment wall, although the same numerical experiments have been performed for a metal bay. At first, radiation was suppressed and an analytical solution for the steady-state problem was obtained (black lines in Figure A2a). The time-dependent solution was obtained using numerical time integration (red lines), showing convergence to the same steady state. Note the dynamic delay in reaching the final solution. Then, the full model including all the radiation terms yielded the green lines, clearly showing a different steady-state solution due to radiation and a significantly larger dynamic delay. The fourth case added maximum solar irradiation of the bay from a direction aligned with a body diagonal of the bay, in yellow.



(**a**) (**b**)

Figure A2. Dynamic temperature excursions for test case; Tbay denotes the bay air temperature, Twi represents the interior wall temperature of the bay, and Twe the exterior wall temperature. (**a**) dynamic excursions, see text above; (**b**) impact of approximations, see text below.

The remaining numerical experiments dealt with approximations, see Figure A2b. If the bay temperature is used in the internal radiation heat transfer coefficient evaluation instead of the internal wall temperature, it has only a minor impact on the solution (light blue lines). If the radiative heat exchange from wall to wall is bypassed and that heat is directly injected into the compartment air, then a larger deviation from the full model solution is observed (dark blue lines). Nevertheless, this approximation still has the same delay time to reach the final solution. Further approximations reduce the use of internal and external wall temperatures, but other disadvantages arise. If the combined heat transfer coefficient from steady-state equilibrium is directly used in the time-accurate simulations, most of the dynamic delay time is lost (orange lines). The same holds for the use of analytical wall temperature expressions (purple lines) derived from the local equilibrium of heat flux terms.

Despite the fact that more variables have to be used and evaluated, the full model is selected to provide the most reliable and complete dynamic thermal excursion modeling.

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