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Cabin Air Quality in Commercial Aircrafts with an Adaptive Environmental Control System Strategy

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Abstract

The current lack of awareness of actual pollutants concentration in the cabin of commercial aircraft makes linking air quality and passenger's comfort problematic, hence dilution with external fresh air is mostly the only adopted approach to assure a good cabin air quality. This manifests in the Environmental Control System (ECS) being the most energy-intensive non-propulsive system. This study reveals that an adaptive ECS with reduced and adjustable fresh air flow ought to save fuel, along with additional sensing and filtering technologies, is capable to maintain a good level of Cabin Air Quality (CAQ). This article simulates single-aisle CAQ, tracking carbon dioxide, and a selected set of volatile organic compounds and particulate matter. Three indicators – well-being impact, measurability, and treatability – have been utilised to prioritize the targeted contaminants. Three main subsystems are modeled using a Modelica framework: the cabin, the recirculation loop and the two pressurisation and air-conditioning kits. The devised models of metabolic and ametabolic generation and deposition of the selected contaminants is able to provide insight on the operation of any ECS architecture and may aid the design of more functional CAQ sensing campaigns.

1. Introduction

The number of passengers flying increases considerably on yearly basis, therefore both the market requirements and the environmental impact of aircrafts shall be taken into account. In this perspective, the Advisory Council for Aeronautics Research and Innovation (ACARE) in Europe mandated that the aviation industry is ought to achieve net-zero emissions by 2050. The work presented in this paper is part of the modelling and simulation effort performed within the Adaptive Environmental Control System[1] (aECS) project funded by Clean Sky 2 program.[2] This project's emphasis is the design of an adaptive ventilation system for an ECS. It is believed that an adaptive ECS might achieve remarkable fuel savings of up to 2% per flight. To get the reader acquainted with the adaptive ECS concept, a summary of the conventional ECS function will be also provided.

The main focus of this paper is on cabin air quality (CAQ) in commercial aircraft since it is of prime interest, especially considering the recent COVID-19 pandemic. The cabin air can be contaminated by sources located both inside and outside. Examples of internal sources are represented by food, cabin materials, and cleaning solvents. Different types of external sources exist, such as ozone and particulate matter (PM). Moreover, external contamination under abnormal conditions includes releases of engine oils, hydraulic fluids, and de-icing fluids. Setting concentration criteria for this many contaminants is challenging since the effects of exposure to pollutants are uncertain. Regulations mostly focus on carbon monoxide, carbon dioxide, and ozone concentrations. The FAA[3] and EASA[4] mandate to deliver at least 0.55 lb/min or 0.28 m^3/min respectively of outside air per passenger in order to prevent cabin pollutants from accumulating. Aircraft air sensing and filtration technologies could improve CAQ and diminish dilution requirements; although, they are not demanded by regulations. Collins Aerospace Ireland Ltd. is developing an adaptive ECS strategy to adjusts the fresh air demand according to the CAQ, which is monitored and controlled by sensors and filters. The resulting air composition differs from the one in a conventionally equipped aircraft.

This article models and simulates CAQ in a single-aisle aircraft during the cruise flight phase. The considered air pollutants are carbon dioxide, Volatile Organic Compounds (VOCs), and PMs. These contaminants have been targeted mainly based on three indicators: how their presence impacts passengers' well-being, and if they are measurable and treatable. The CAQ is analyzed under two control options: a conventional system, employing a prescribed amount of fresh air, against an adaptive strategy, relying on CAQ sensing and air filtration. A Modelica environment is used for

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the integrated modelling and simulation of three main sub-systems. The cabin model evaluates thermo-hygrometric conditions and air quality based on the number of passengers and crew, outdoor conditions, and fresh air quality. The recirculation loop model comprises the fan, filters, and mixing chamber. The PACK is modeled with heat-exchangers and turbomachinery for the conditioning of hot bleed air.

Today, inadequate understanding of interior pollutant concentrations makes it hard to link air quality with passengers' and cabin crew's comfort. To make things more challenging, there is no standard method for assessing CAQ. Air filtration and sensing are not required by FAA or EASA regulations. Thus, cabin air pollutants are rarely monitored or filtered during flight, and the only option to avoid their accumulation is dilution with exterior air. Conventional ECS is the most energy-intensive non-propulsive system in an aircraft since it demands a predefined amount of fresh air. This study reveals that an adaptive ECS with reduced and adjustable fresh air flow ought to save fuel, along with additional sensing and filtering technologies, is capable to maintain a good level of CAQ. A new ECS architecture that alters fresh air flow rate based on CAQ will change the regulations' requirements, and it will position civil aviation for a more sustainable future.

The remainder of the paper is outlined as follows: firstly the conventional and adaptive ECS architectures are introduced in Section 2.1 and 2.2 respectively, in Section 3 the selected contaminants modelling is formulated and their control thresholds and priorities are described, in Section 4 the main findings are represented and discussed, and finally in Section 5 the main outcomes are drawn and future research recommendations are advised.

2. Environmental control system architectures

The Environmental Control System (ECS) pressurizes and conditions air for crew and passengers. This system must meet pressure, temperature, and air flow standards, especially at high altitude where humans strive to survive. Air sources, pressurization and air conditioning kits (PACKs), a distribution system, and control units constitute the ECS. Follows a brief description of the conventional and adaptive ECS architectures.

2.1 Conventional ECS

A traditional ECS uses pneumatic or electrically compressed air. The engine compressor, auxiliary power unit, or ground services compress air in a pneumatic (bleed) ECS, depending on mission state. The pneumatic ECS consumes 75%[5] of non-propulsive power during cruise and from 3% to 5% of engine power. Energy is needed to compress outside air that enters the compressor stages of the engine core, and some of this air is evacuated as bleed air, which reduces thrust. Similarly, an electric ECS compresses air from the atmosphere using an engine-driven electric compressor. Boeing 787s use this latest technology. Although, for equal amounts of energy extracted from the engine, direct power off-take has a higher Specific Fuel Consumption (SFC) than just bleed air extraction.[6] Therefore, air bleeding outperforms power off-take from engine performance perspective. Electric ECS uses less energy than regular ECS. Since energy extraction affects the engine less, electric ECS are more efficient for large aircraft with long flights. Actuated flow control valves regulate compressed air in both ECS architectures. The air-conditioning PACKs, one per engine, receive compressed air from the engine or electric compressor. Apart this source difference, the two systems' designs are equivalent. A representative diagram of a conventional ECS is depicted in Figure 1.

Air-conditioning packs use outside cold air as refrigerant. The ram intake brings this air into the aircraft. A turbine-compressor machine, valves for temperature and flow control, and heat exchangers that lower compressed air temperature through the ram enable air conditioning. The cabin's air is regulated by the air-conditioning pack. Outside airflow is influenced by temperature regulation: the temperature controller adjusts valves based on flight characteristics such as aircraft altitude, zone temperature set-points, and cabin zone temperature to maintain a comfortable environment in normal situations. To maintain cabin pressurisation and minimise excessive structural loads, the outside air flow is controlled. Air from the pack mixes with filtered recirculated air in a mixing chamber; usually a 50% outdoor air and 50% recirculated air mix is operated. The mixing manifold receives sterile air from cabin air filters in the recirculation loop upstream of the mixing chamber. Current ECSs use a prescribed amount of fresh air per passenger (0.55 lb/min/pax[4]) to dilute contaminants generated in the aircraft cabin, provide adequate oxygen, and maintain cabin pressurisation to ensure a safe, comfortable, and below-threshold contaminants levels. Modern aircraft only control ozone, not cabin air quality, since high elevations have high ozone levels. The ventilation system distributes mixed air to the cabin. Air arrives via overhead distribution outlets along the cabin. To provide comfort without drafts, precise airflow patterns are needed due to the large mass flow rate of air entering the cabin's constrained volume. The distribution system also reduces airflow in the fore and aft directions since cabin occupants carry viruses and bacteria. Half of the cabin air is released outboard through outflow valves to maintain cabin pressure. The rest is filtered and combined with fresh air in the mixing chamber.

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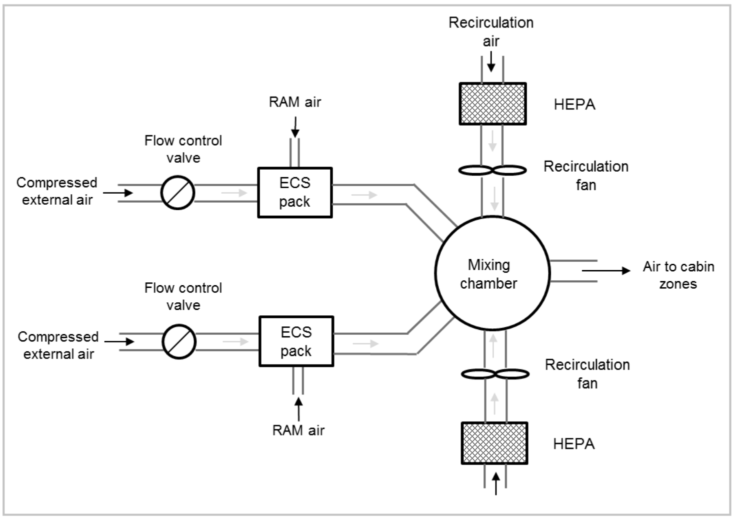

Figure 1: Representation of a conventional ECS architecture with left and right PACKs and recirculation, modified from Quartarone et al.[1]

2.2 Adaptive ECS

An Adaptive Environmental Control System (aECS) is an ECS with adaptive external air flow regulation. As in the conventional architectures described in Section 2.1, the adaptive systems provide conditioned air to aircraft personnel and passengers and must meet pressure, temperature, and air flow requirements. However, in addition to the components presently installed in a conventional ECS, an aECS comprises technologies for air filtration and sensing. The concept underlying aECS is applicable to both bleed and electric systems. Such system is represented in Figure 2.

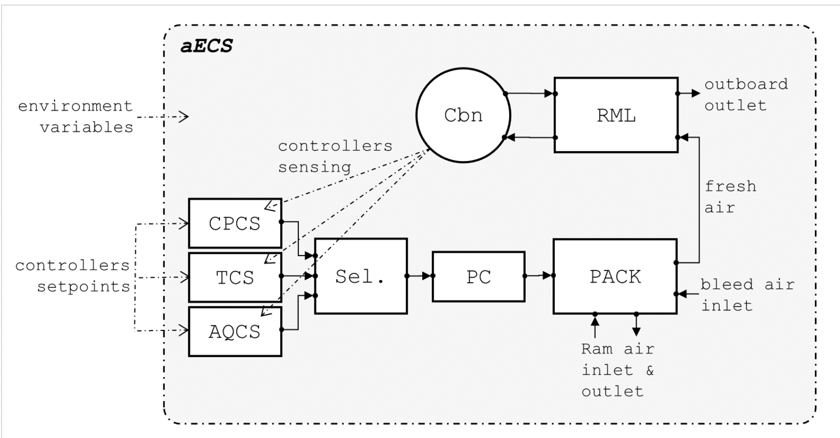

Figure 2: Representation of the adaptive ECS architecture: the various components acronyms are listed in Table 1.

The adaptive ECS specifically depends on the development of sensing and filtering technologies able to detecting and removing respectively contaminants in all states and maintaining them below hazardous levels. These technologies along with a cabin air quality control, that regulates air treatment and optimises the mixing between fresh and recirculated air, are captured in a system level architecture model to address various concepts of operation.

3. Contaminants modelling and control

In the scope of the adaptive ECS project's simulator, it is critical to model the air quality within the controlled cabin environment. Contaminants generation phenomena are several: the pollutants may come from the atmospheric air composition at the specific considered flight phase – e.g., ozone levels –, or may be generated by the engine operation – e.g., fuel or hydraulic fluids –, or within the cabin might be the result of the passengers' metabolism – such as CO2.

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Table 1: Definition of the aECS components' acronyms as by aECS diagram of Figure 2

acronym	**components**	**function description**
PACK	Pressurisation & Air-Conditioning Kit	provides the requested fresh air to the RML subsystem
RML	Recirculation Mixing Loop	filters a portion of Cbn air and mixes it with fresh air
Cbn	Cabin	is the main controlled volume
PC	Pack Controller	a neatly designed PI control for the PACK operation
CPCS	Cabin Pressure Control System	regulates the pressure within the Cbn
TCS	Temperature Control System	regulates the temperature in Cbn
AQCS	Air Quality Control System	uses CAQ information to provide a demand estimate to Sel.
Sel.	Selector	high-level control which uniquely defines the PACK demand

The fourteen targeted compounds, along with their modelling parameters and literature information sources, are stored in Table 2. The specifics of such content is presented in detail in the following sections. The contaminants generation phenomena have been calibrated for the specific modelled aircraft in the aECS project, however the presented methodology can be applied to any other aircraft with a pressurized and air-conditioned cabin. Unfortunately, it is important to acknowledge that there is a general lack of experimental data on the quantitative and qualitative levels of CAQ in commercial aircraft. Furthermore, recent sensing technologies are not utilised in most studies.

Table 2: Selected contaminants' ametabolic generation rates and their relevant literature references, where C_i is the concentration of the ith pollutant, $\bar{C}_i$ are its average values, $\hat{C}_i$ its maximum registered peak value, and $\dot{C}_i$ is its modeled bleed generation rate.

contaminant name	**symbol**	$\dot{\mathbf{C}}_\mathbf{i}$ ^{a} [μg · m^{-3}· s^{-1}]	$\bar{\mathbf{C}}_\mathbf{i}$ [μg · m^{-3}]	$\hat{\mathbf{C}}_\mathbf{i}$ [μg · m^{-3}]	**reference**
carbon monoxide	CO	1.84×10^3	$(0.5^-, 2.0)$ [ppm]^b	13.0 [ppm]^c	7–10
benzene	B	1.61×10^1	$(0.72, 16.1)$	1.45×10^2	7, 11–13
toluene	T	3.07×10^1	$(3.01, 30.66)$	2.37×10^2	7, 11–13
ethyl-benzene	E	7.20	$(0.14, 7.23)$	4.51×10^1	7, 11–13
xylene -m -p	Xmp	4.60	$(0.49, 4.60)$	7.07×10^1	7, 11–13
xylene -o	Xo	6.10	$(0.16, 6.10)$	6.29×10^1	7, 11–13
(ortho) tricresyl phosphate	ToCP	2.07	$(6.00 \times 10^{-4}, 2.07)$	5.13×10^1	11, 14
tri (i) butil phosphate	TiBP	2.00	$(0.11, 2.00^-)$	1.09×10^1	11, 15
tri (n) butil phosphate	TnBP	6.40	$(1.10, 6.40)$	3.50×10^1	7, 10, 16
propylene glycol	PG	1.15	$(1.15, 2.00^-)$	3.60×10^2	7, 14, 17
ultra-fine particulate ($\leqslant 0.1\mu$m)	$PM_{0.1}$	$6.49\ ^d$ $0.00\ ^e$ $3.65 \times 10^4\ ^f$	$(3.41, -)\ ^d$	$1.09 \times 10^2\ ^d$	18–21
medium particulate ($\leqslant 2.5\mu$m)	$PM_{2.5}$	$7.36\ ^d$ $3.33 \times 10^{-2}\ ^e$ $1.82 \times 10^5\ ^f$	$(3.80, -)\ ^d$	$3.65 \times 10^1\ ^d$	18–21
large particulate ($\leqslant 10\mu$m)	PM_{10}	$1.17 \times 10^1\ ^d$ $1.00 \times 10^{-1}\ ^e$ $1.82 \times 10^6\ ^f$	$(4.90, -)\ ^d$	$4.78 \times 10^1\ ^d$	18–21

^{a}Evaluated generation rate; ^{b}i.e. $\sim (0.47, 1.89) \times 10^3 \mu\text{g} \cdot \text{m}^{-3}$; ^{c} i.e. $\sim 12.29 \times 10^3 \mu\text{g} \cdot \text{m}^{-3}$
^{d}Conversion from particulates count per m^3 considering their average composition
^{e}PMi generation rate within the cabin [μg · m^{-3}· s^{-1}· pax^{-1}]; ^{f}PMi deposition rate on cabin surfaces [μg · s^{-1}].

3.1 Carbon dioxide model

The total metabolically generated amount of CO_2 within the cabin, expressed as C_{CO_2} in [kg/m^3], follows the law in equation (1)[22]

$$\begin{cases} \frac{\mathrm{d}C_{CO_2}}{\mathrm{d}t} = \frac{\rho_{\text{air}} \cdot N_{\text{tot}} \cdot r_{CO_2}}{3.6 \times 10^3} \\ r_{CO_2} = r_{CO_2\text{ref}} \cdot \frac{d_{\text{ref}}}{\rho_{\text{air}}} \end{cases} \tag{1}$$

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where $r_{CO_2 ref} = 20$ [h^{-1}][22] is the reference generation rate per passenger, $d_{ref} = 1.19$ [kg/m^3][22] is the reference CO_2 density, r_{CO_2} is the normalised CO_2 generation rate per passenger in [$h^{-1} \cdot pax^{-1}$], N_{tot} is the total number of people in the cabin (crew and passengers). While the indoor metabolic generation rate is function of the number of passengers, the external source of CO_2 – e.g., coming from the air bled from the engine – varies with the external environmental conditions but at cruise can be considered steady at 5.77×10^{-4} kg/m^3.[22] The two generation rates are dynamically combined in the mixing manifold where a portion of the exhaust cabin air is added to the fresh air flow provided by the pack. The amount of CO_2 added back to the supply is not only function of the metabolic generation rate and recirculation flow rate, but it is also affected by eventual CO_2 filtration technologies installed in the recirculation pipe.

3.2 Volatile organic compounds models

The selected volatile organic compounds (VOCs) are subdivided as follows: *carbon monoxide* (CO), the aromatic *BTEX* group, some *organophosphates* (OPs), and the deicing fluid *propylene glycol* (PG). The hereby studied BTEX comprise *benzene*, *toluene*, *ethyl-benzene*, and all three isomers of *xylene* – i.e., *iso* (i), *ortho* (o), and *meso* (m). The identified OPs consist of: *tricresyl phosphate* (ToCP, only the toxic *ortho* isomer) present in engine oil, and the two isomers of hydraulic oil *tributyl phosphate* (TiBP and TnBP). The adopted ametabolic VOC generation rate model is quite simple as shown in equation 2.

$$\frac{\mathrm{d}C_{\mathrm{VOC}i}(t)}{\mathrm{d}t} = \dot{\mathbf{C}}_\mathbf{i} \tag{2}$$

where estimated value of the external ametabolic generation rate, $\dot{\mathbf{C}}_\mathbf{i}$, is stored for each VOC in Table 2. Although, despite the simplistic model located at the bleed intake, the total compound dynamics of the VOCs, as any other contaminant, are function of the recirculation fraction as formulated in equation 3.

$$\begin{cases} \frac{\mathrm{d}C_{\mathrm{o}i}(t)}{\mathrm{d}t} = \gamma(t)\frac{\dot{m}_\mathrm{b}}{\dot{m}_\mathrm{r}} \cdot \dot{\mathbf{C}}_\mathbf{i} - \gamma(t) \cdot C_{\mathrm{o}i}(t) \\ \gamma(t) = \frac{\dot{m}_\mathrm{r}}{\dot{m}_\mathrm{r}+\dot{m}_\mathrm{b}} \end{cases} \tag{3}$$

where C_{oi} ($\mu g/m^3$) is the concentration of the ith VOC in the occupied zone, γ is the air recirculation rate, and the mass flow rates $\dot{m}$ subscripts are respectively *recirculation* (r) and *bleed* (b).

3.3 Particulate matter models

The modelled particulate matter (PM) are conventionally subdivided in three groups: ultrafine particles with size smaller than 0.1µm ($PM_{0.1}$), small particles less than 2.5µm ($PM_{2.5}$), and the largest particles of up to 10µm (PM_{10}). The most relevant referenced study, by Cao et al.,[18] about aircraft cabin dynamics is actually focused on modelling the deposition of the particles on the cabin air supply, deriving the conclusion that these ducts must be cleaned about every six months. In the considered study it was intended to model all the sources of $PM_{2.5}$ and PM_{10}, which is of our interest. Three main aspects of PM dynamics are considered: the condition of the air outside the aircraft – i.e., bleed air source –, within the cabin the generation proportional to the number of passengers, and the deposition rate on cabin surfaces. Moreover, experimental data that illustrate the concentration changes due to seasons (fall, winter, spring, summer) and flight phases (boarding and deplaning, sitting on the ground, ground services, meal servicing, sitting in the air) are also provided, althought this is out of scope of the current modelling activity. The equation (4) combines all the contributions in three ODEs, one for each ith PM_i. However, in line with our adopted modelling methodology – i.e., lump-volume representation of the ECS in Modelica environment – the three generation/deposition rates are defined in separate respective models according to where the phenomena is taking place.

$$\frac{\mathrm{d}C_{\mathrm{o}i}(t)}{\mathrm{d}t} = \lambda \cdot C_{\mathrm{s}i}(t) - \lambda \cdot C_{\mathrm{o}i}(t) - K_i \cdot C_{\mathrm{o}i}(t) + \frac{S_{\mathrm{c}i}(t)}{V_i} N \tag{4}$$

where C_{oi} ($\mu g/m^3$) is the concentration of the ith particle (e.g. $i = 0.1$ for $PM_{0.1}$) in the occupied zone, λ (h^{-1}) is the air exchange rate for the cabin, C_{si} ($\mu g/m^3$) is the ith particle's concentration in the supply air, K_i is the deposition rate on the cabin surfaces, S_{ci} (µg/h per person) is the ith particle emission rate per person from in-cabin sources in, and N is the total number of people – i.e., passengers and crew. These generation and deposition rates are store in Table 2. Cao et al.[18] gathered measurement data on MD82, B737/A320 and B777. Therefore every model parameter had to be reasonably adjusted for the specific aircraft application of the aECS project. For instance, the deposition rates depend on the actual inner surface so this parameter was calibrated proportionally to the estimated interiors' surfaces.

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3.4 About control thresholds and priorities

The air quality control system monitors and controls the levels of contaminants concentration within the cabin. The developed AQCS contains an algorithm that provides two main information to the controller. Firstly it has an understanding of the most likely source of each contaminants – i.e., if it is ametabolically originated externally from air bled from the engine, or if it is metabolically generated within the cabin by the passenger's activity. Secondly it assigns the proper priority to the sensed contaminants according to a preset criteria. The contaminants priority is mainly decided based on how their presence impacts passengers' well-being, and if their maximum exposure thresholds are currently regulated worldwide. The Table 3 allows the definition of the AQCS contaminants priorities and regulatory thresholds, along with providing their well-being hazard types and the sources of such information. Unfortunately, not all the considered contaminants are regulated. Therefore, as shown in Table 3, some thresholds are informed guess values, evaluated by extrapolating the correlation between steady state cabin concentration and threshold of other regulated pollutants in the same contaminants family. For instance, the ethylbenzene and xylene thresholds where calculated based on the toluene information, while the PM_{10} on the other PMs' thresholds.

Table 3: Selected contaminants' assigned priorities, regulatory thresholds, and well-being hazard types.

contaminant	**priority**	**threshold** [$\mu g/m^3$]	**threshold** [ppm]	**hazard type**	**reference**
CO_2	1[a]	7.23×10^6	5.00×10^3	toxic[23]	4
CO	2	7.00×10^3	7.61×10^0	toxic[23]	24
B	3	1.70×10^1	6.63×10^{-3}	carcinogenic, toxic[23]	24
T	8	1.51×10^2	5.00×10^{-2}	toxic[23]	25, 26
E	9	6.97×10^1	2.00×10^{-2}	toxic[23]	⋆
Xmp	10	3.49×10^2	1.00×10^{-1}	toxic[23]	⋆
Xo	11	3.49×10^2	1.00×10^{-1}	toxic[23]	⋆
ToCP	5	2.00×10^1	1.65×10^{-3}	irritating, toxic[23]	27, 28
TiBP	6	5.83×10^2	6.67×10^{-2}	irritating, toxic[23]	29, 30
TnBP	7	1.75×10^3	2.00×10^{-1}	irritating, toxic[23]	29, 30
PG	12	1.25×10^2	5.00×10^{-2}	low toxicity[23]	31, 32
$PM_{0.1}$	4	2.84×10^1	3.98×10^{-3}	carcinogenic[23]	19
$PM_{2.5}$	13	1.20×10^1	6.25×10^{-3}	irritating[23]	33–35
PM_{10}	14	4.00×10^1	2.08×10^{-2}	irritating[23]	⋆

[a]highest priority; ⋆these values are informed guesses.

4. Results and discussion

Following the calibration of the contaminants' generation models, formulated in the previous Section 3, against their asymptotic values, the ECS and aECS responses to critical events from CAQ perspective were tested for each selected pollutant. For instance, unexpected metabolic or ametabolic generation of contaminants within the cabin or fume events coming from the engine-bled air were simulated. Two exemplary contaminants dynamics are shown hereby to depict the two behavioural trends: a sudden generation of CO_2 within the cabin that may be caused by increased activity level of the passengers, and a critical rise of benzene concentration that may be liked to a fume event.

With regards to the CO_2 case, a threefold rise of its generation rate per passenger was simulated starting at time $t = 5000$ s and released to its normal values at $t = 8000$ s. The conventional ECS and adaptive ECS responses are represented in Figure 3 and Figure 4 respectively. In the conventional operation case, the CO_2 concentration is never above the 5000 ppm threshold, while for the aECS, receiving a reduced fresh air flow from the PACK, the CO_2 level is maintained right at the threshold value thanks to the AQCS intervention. The fact that in the ECS case the CO_2 is below threshold is just a fortunate case: in fact, for an even larger generation rate of CO_2 (or any other contaminant generated within the cabin) the concentration can overshoot the threshold. The conventional ECS, not having any sensing technology, would not be able to detect such event and the PACK would keep operating at the same regime without being able to properly dilute the contaminant. The aECS instead, would always be able to inform the PACK controller to provide the right amount of fresh flow to accordingly dilute the troublesome contaminant; this is in the limits of the PACK operation capacity. Please note in Figure 4 that at *t1* there is a switching between conventional and adaptive operation of the ECS, this is to highlight the fact that the designed aECS fuel-saving strategy can be activated according to the mission envelope requirements. This means that in the region (a) the fresh air mass flow rate is assigned to be the

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scheduled amount, while as soon as the adaptive control is switched on, in the following regions (b) to (d) the TCS and AQCS are the controllers that limit the PACK demand in normal operating conditions.

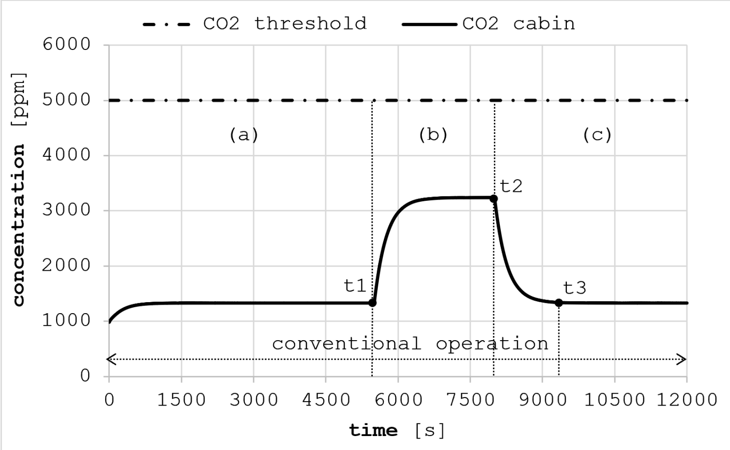

Figure 3: CO2 critical event dynamic in a conventional ECS. At time (t1) there is a sudden rise of the CO2 metabolic generation rate within the cabin, kept constant in region (b) and then returned to the usual CO_2 generation rate in region (c).

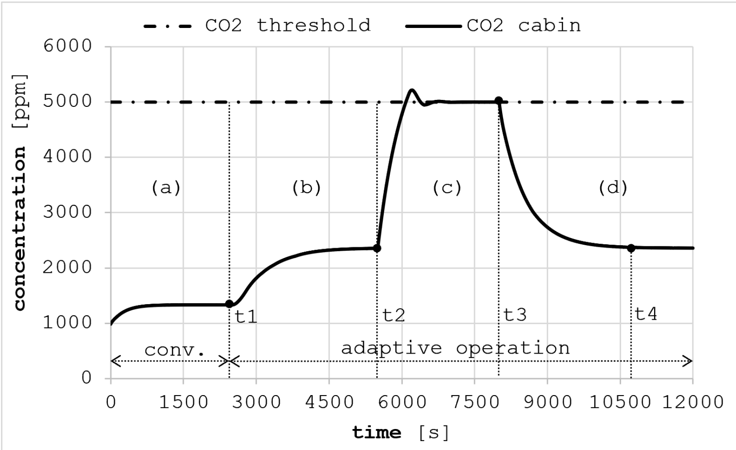

Figure 4: CO_2 dynamics as a result of the AQCS response to a sudden threefold rise of the CO2 metabolic generation rate within the cabin (c). In the region (a) reaches a steady state at 1331 ppm under a conventional ECS operation with a scheduled mass flow rate per person, while the remaining regions the ECS follows the adaptive strategy with asymptotic concentration of 2351 ppm. Regions (b, d) are limited by the TCS while event (c) is controlled by the AQCS (refer to Figure 5).

Comparing Figure 3 and Figure 4 one can notice that the dilution time – i.e., time needed to return to normal contaminant's concentration from the event's peak value – for the conventional ECS ($t_d = t_3 - t_2 \simeq 1250$ s) is shorter than the adaptive one ($t_d = t_4 - t_3 \simeq 2600$ s). This is to be expected since the unpolluted fresh air mass flow rate provided by the PACK in the conventional ECS – i.e., the *scheduled* amount according to the current regulations – is larger than the one required by the TCS in the adaptive ECS – i.e., about 48% of the schedule value according to Figure 4. This does not necessarily need to be considered as a negative feature of aECS: the level of CO_2 is promptly kept under the threshold value of 5000 ppm and it avoids to unnecessarily overload the PACK operation with a large fresh air demand. In other words, the adaptive ECS indirectly saves fuel while being able to satisfy the CAQ requirements for contaminants generated within the cabin even in case of sudden rise of their generation rate.
To clarify how the TCS, AQCS and PACK controller interact in an aECS, Figure 5 represents the responses of the temperature and air-quality controls to the event dynamics of Figure 4. In normal cruise condition (regions b and d), the TCS is the control limiting the fresh PACK flow, and the PACK flow demanded by the AQCS is visibly lower thanks to the good level of measured CAQ. Then at time *t2* the critical event takes place. The CO_2 level rises until

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overshooting the threshold, hence at this point the AQCS starts demanding more from the PACK in order to readily dilute it. This is in line with the information provided by the internal algorithm that the CO_2 is metabolically generated within the cabin. Finally, when the event terminates at time *t3*, the TCS returns to be the limiting controller on the PACK flow. Note that in this discussion the CPCS, even if it is part of the control architecture, it is not considered. This is because in normal ECS operation, its demand is at all time the lowest, never overcoming the TCS and AQCS requests.

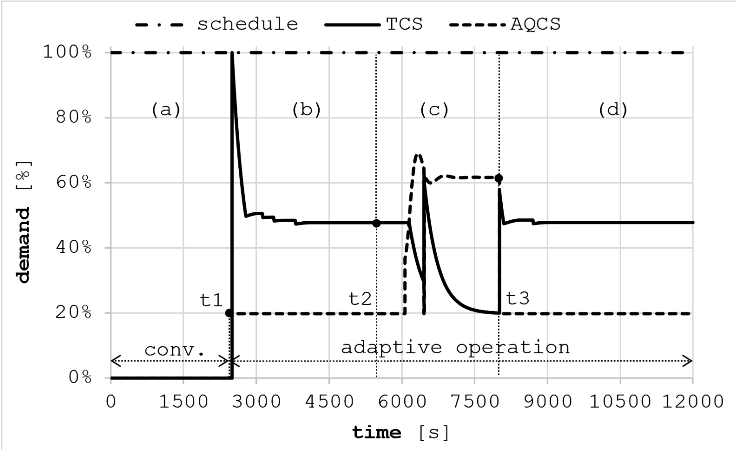

Figure 5: Relative TCS and AQCS demands with respect to a scheduled 0.55 lb/min/pax of a conventional ECS (a). In (b, d) the fresh air demand is limited by the TCS at approximately 48% the scheduled mass flow; while during the sudden CO_2 event (c), overshooting the regulatory threshold triggers the AQCS at 62% of schedule, hence dominating the fresh air flow demand.

Similarly to the CO_2 case, a fume event was simulated focussing on the responses of the conventional and adaptive ECS to a sudden rise of benzene concentration in the cabin, as represented in Figure 6.

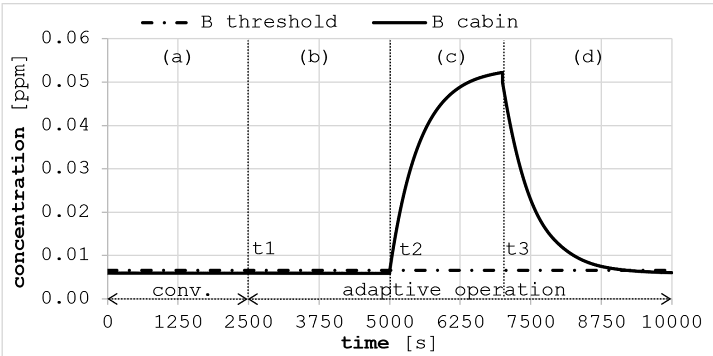

Figure 6: Benzene dynamic dilution response with (a) conventional ECS operation with scheduled mass flow rate per person, while the remaining regions are adaptive ECS operation. The peak generation rate is according to the maximum values, $\mathbf{\hat{C}_i}$, stored in Table 2.

All the contaminants listed in Table 2 follow the same dynamic behaviour, so the following discussion is valid for all the remaining pollutants ametabolically generated before the PACK inlet. To understand what is happening in this event case, it is important to consider that the selection of fresh flow demand to the PACK controller follows a prioritization between controllers. In terms of cabin safety and comfort, the pressure is considered to be the most critical property to be kept normally around 0.8 bar during cruise flight phase. Second in importance is considered to be the temperature comfort, followed at last by the CAQ level. Therefore, pressure and temperature set points cannot be compromised for a better air quality. Consequently, both conventional and adaptive ECS would behave in the same way with contamination either originated from outside of the aircraft or within the engine, while essentially by different reasons: the ECS would ignore the threat because of not being equipped with sensing technology, while the aECS cannot reduce the fresh PACK flow, as the ACQS would suggest, because this would result in an unwanted increase of temperature in the cabin. In other words, even if the AQCS does request a smaller external flow rate, the

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TCS is the limiting controller here requiring a larger demand from the PACK, as depicted in Figure 7 regions from *b* to *d*. Hence, anomalies of the external contaminant sources cannot be compensated by the AQCS as long as the thermal comfort is considered to be a priority over the cabin air quality.

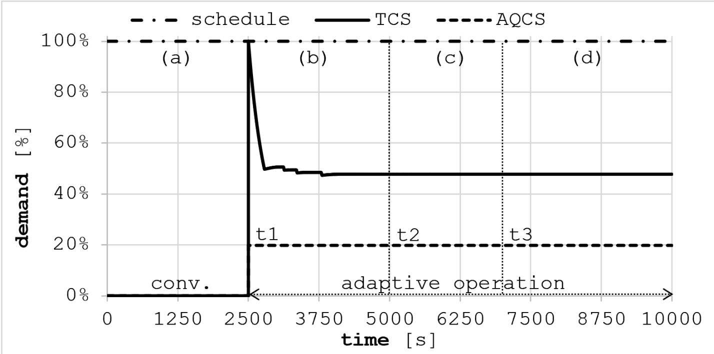

Figure 7: Benzene dynamic controllers response with (a) conventional ECS operation with scheduled mass flow rate per person, while the remaining regions are adaptive ECS operation with fresh air demand constrained by the TCS in all cases.

5. Conclusion

In this paper we proposed a modelling of CAQ dynamics in the frame of the EU-funded Adaptive Environmental Control System project. The information on CAQ gathered from literature was partially incomplete, missing or, in some cases, intuitively too conservative. This is caused by two main reasons: on the one hand, the approach of the past measurement campaigns was not sufficient to provide dynamics information or relevant correlations with known contaminants; on the other hand, there are no regulations available to support certification of aECS in terms of cabin air quality with the depth proposed in this paper. In light of the current circumstances, we would advise to design more on-point measurement campaigns with supporting sensing technologies, then leverage the monitoring results to initiate a collaboration with regulatory agencies – e.g., FAA and EASA – to accelerate the standardization of cabin air quality. This in turn would also allow a clearer and more focused design of future sustainable solutions related to the ECS. Despite the current limitations, we managed to formulate some preliminary dynamic models of the fourteen selected contaminants: carbon dioxide, carbon monoxide, BTEXs – i.e., benzene, toluene, ethylbenzene and xylene compounds –, some organophosphates, propylene glycol, and all particulates. The models were calibrated so to have the steady state contamintant's concentration in the cabin equal to the expected concentrations during normal flight conditions in cruise. The response of the adaptive strategy to adverse events – e.g., fume events – was also investigated. What was noticed is that in case of sudden increase of generation of metabolic compounds within the cabin, such as CO_2, the Air Quality Control System (AQCS) responds promptly to the emergency requesting more fresh air from the pack in order to dilute quicker the contaminant. Although, in the case of critical events of externally sourced ametabolic contaminants, even if the AQCS does request a smaller external flow rate, the Temperature Control System (TCS) is the limiting controller here requiring a larger demand from the PACK. Hence, anomalies of the external contaminant sources cannot be compensated by the AQCS as long as the thermal comfort is considered to be a priority over the cabin air quality. All considered the devised models of metabolic and ametabolic generation and deposition of the selected contaminants is still able to provide insight on the operation of any ECS architecture and can perhaps aid the design of more functional CAQ sensing campaigns.

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