Modeling of aircraft fire suppression system by the lumped parameter approach

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Abstract
Purpose – This paper aims to determine the halon concentration time-evolution inside an aircraft cargo compartment to design fire extinguishing systems.
Design/methodology/approach – A fire suppression system is numerically simulated using the lumped parameter approach.
Findings – The halon volumetric concentration, halon and air mass fluxes and the cargo compartment pressure are numerically calculated. It also determines the time to halon concentration to achieve the fire suppressant value (high pressure bottle) as well as its inerting volumetric concentration (low pressure bottle).
Research limitations/implications – In the lumped parameter approach, the dependent variables of interest are a function of time alone, and its spatial distribution is neglected.
Practical implications – This study predicts the fire extinguishing agent behavior aiming to satisfy cargo compartment certification requirements.
Originality/value – This paper uses a simplified methodology, but it represents a very useful tool during the preliminary stages of the aircraft fire suppression systems design.

Keywords Fire extinguishing, Fire suppression, Halon, Lumped parameter approach

Paper type Technical paper

Introduction

Cargo compartments in large transport aircrafts present a potentially severe fire problem because of the large quantity and great variety of combustible materials carried in passenger luggage, mail and cargo, including hazardous materials (Lombardo, 1998).

In large transport aircraft, the cargo compartments are located in the belly of the aircraft beneath the floor of the passenger cabin, requiring built-in design features such as fire suppression and detection systems (Moir and Seabridge, 2001). A typical fire suppression system provides a fire extinguishing agent through short, highly pressurized feedlines. Tubing connects the bottles to discharge nozzles in the cargo compartment ceilings and a halogenated hydrocarbon (e.g. halon) is commonly used. The rapid discharge rate not only delivers the suppressant agent but also pressurizes the compartment zone, which interrupts the normal flow of ventilating air, robbing the fire of its oxygen (Lombardo, 1993). On the other hand, the fire detection systems are currently based on smoke detectors. Besides, the survivability of an aircraft in a fire scenario depends on this early detection of the fire (Chen *et al.*, 2007). However, some fires are not detected, and consequently the systems may not be considered reliable. Thus, a great flexibility and high reliability are required for flame and smoke detection algorithms, to reduce the false alarm rate and to decrease the alarm reaction time (Han and Lee, 2009). The actual ratio of false alarms to real fires is about 10:1 (Kallergis, 2001).

The purposes of detectors and fire suppression systems are to contain the fire within the cargo compartment, protect flight critical systems and prevent passengers and crew from being subjected to hazardous quantities of smoke and toxic gases, so the aircraft can be landed safely (Blake *et al.*, 1998; Blake, 2006).

According to the literature (Lombardo, 1993), three key benefits of gaseous fire suppression should be high permeability, rapid mixing and total penetration of protected areas and equipment. Usually, extinguishing agents fall into two categories: halogenated hydrocarbon (halon) agents and the inert cold-gas agents. The halogens used to form extinguishing compounds are fluorine, chlorine and bromine. Halogenated agents put out fire by causing a chemical interference in the combustion process between the fuel and the oxidizer. Inert cold-gas agents include carbon dioxide (CO_2) and nitrogen (N_2). Both agents are readily obtainable in either gaseous or liquid forms. For more than 30 years,

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halocarbon suppressant agents as Halon 1,301 has been used in the fire suppression system (NFPA, 1997).

The fact that Halon 1,301 installations were very easy to design and install and that halon was available to everybody on a low-cost basis supported the tremendous success of Halon 1,301 for fire protection applications for many years. While the economy was growing strongly, environmental arguments were neglected and were not the subject of scientific interest as nowadays. However, sensitivity to environmental matters, discussions on global climate change and the ozone holes in the stratosphere induced a change of attitude to halon, as it was found out that they have a very long lifetime in the stratosphere and are one of the major influences on the destruction of our stratospheric ozone layer.

In 1987, the first international conference on global environmental protection was held in Montreal with the key objective of banning the production of environmentally unfriendly substances. The final document, known as the Montreal Protocol, regulations were proposed on the production of Halon 1,301. Presently, the Montreal Protocol has been signed and implemented by most of the world's industrial and developed countries. In the Montreal Protocol, the production and the distribution of Halon 1,301 is strongly limited allowing access to more environmentally friendly substances which has led to a total change in the market for new fire suppression systems.

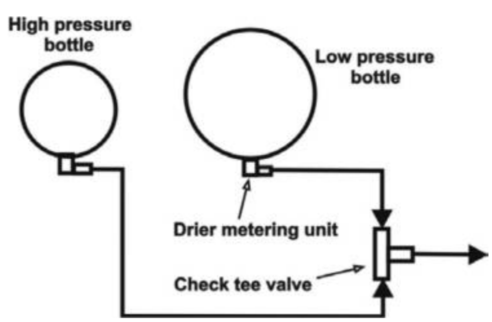
Essential applications such as military installations, nuclear power plants or aircraft are not covered by the Montreal Protocol. As long as no better alternatives are found, the use of halon is still authorized in these exception cases (Niu *et al.*, 2013). Since the signing of the Montreal Protocol, extensive efforts have been devoted to the search for halon alternative to replace Halon 1,301 (Yang *et al.*, 1996). Several hydrofluorcarbons and perfluorcarbons have been developed as candidate halon replacements (Saso *et al.*, 1996).

The fire suppression system of the cargo compartment consists of an initial discharge of a fixed quantity of agent followed by a metered system that added agent to maintain a minimum concentration. This system is composed by two bottles: high and low pressures recipients (Figure 1). The quantities for the initial discharge and the subsequent minimum design concentration that were maintained were based on the current industry practice: 5 per cent initial concentration of Halon 1,301 in an empty cargo compartment volume to suppress any combustion to controllable levels and 3 per cent concentration for the duration of the flight to prevent re-ignition or spreading of the combustion. For airplanes certified for Extended-range Twin-engine Operations, the fire-suppression system must be able to sustain a 3 per cent inerting concentration of halon within the compartment for all the extended time-flight.

In a conventional in-flight, the halon fire extinguisher bottle has a fixed amount of agent that is initially dispensed to the bottle followed by pressurization with nitrogen to a desired equilibrium pressure at room temperature. The amount of agent and the charged pressure can be varied according to the application.

In this context, the present study uses the lumped parameter method for determining the halon volumetric concentration time-evolution inside an aircraft cargo compartment. The time to halon concentration to achieve the fire suppressant value (high pressure bottle) as well as its inerting volumetric concentration (low pressure bottle) are also calculated.

Figure 1 Typical fire suppression in an aircraft cargo compartment: low pressure bottle; high pressure bottle; Drier Metering Unit (DMU) and check tee valve



Mathematical modeling: fire suppression system

Penteado (2004) carried out an experimental set-up to test the behavior of a typical cargo compartment fire suppressant system. In their experimental chamber, the outflow valves are closed during the halon discharge. So the exit mass flow rate ($\dot{m}_E$) corresponds to the mixture flow (air + halon) through the cargo compartment wall leakages. A simplified control-volume model to characterize this experimental set-up is presented in Figure 2.

Halon and air masses time-variation are mathematically modeled by the differential equation system represented by equations (1 and 2). This system was obtained applying the mass conservation law and a lumped parameter approach, as follows:

$$\frac{dm_H}{dt} = \dot{m}_H - \dot{m}_E(C_H) \tag{1}$$

$$\frac{dm_{AIR}}{dt} = \dot{m}_{AIR} - \dot{m}_E(C_{AIR}) = \dot{m}_{AIR} - \dot{m}_E(1 - C_H) \tag{2}$$

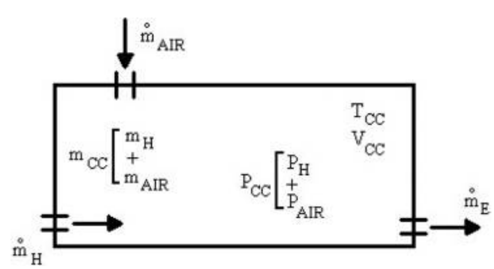
with:

$$C_H = \frac{m_H}{m_{CC}} = \frac{m_H}{m_H + m_{AIR}} \tag{3}$$

and:

$$C_{AIR} = \frac{m_{AIR}}{m_{CC}} = \frac{m_{AIR}}{m_H + m_{AIR}} \tag{4}$$

Figure 2 A based control-volume model for the air-halon mixture flow inside the aircraft cargo compartment



where:

m_H = halon mass stored in the cargo compartment;
m_{AIR} = air mass stored;
m_{CC} = mixture mass stored;
$\dot{m}_H$ = halon input mass flow rate;
$\dot{m}_{AIR}$ = air input mass flow rate;
$\dot{m}_E$ = mixture (air + halon) leakage mass flow rate;
C_H = halon mass concentration; and
C_{AIR} = air mass concentration.

Considering compressible airflow through orifices (SAE, 2000a, 2000b), the cargo compartment leakage mass flow rate can be determined by using equations (5 and 6):

$$\dot{m}_E = CA\sqrt{2\frac{\gamma}{\gamma\ 1}\rho_{CC}P_{CC}\left[(rp)^{\frac{2}{\gamma}}\ (rp)^{\frac{\gamma+1}{\gamma}}\right]},\ \text{if rpc} \le \text{rp} \le 1 \tag{5}$$

or:

$$\dot{m}_E = CA\sqrt{\rho_{CC}P_{CC}\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma\ 1}}},\ \text{if rp} < \text{rpc} \tag{6}$$

with:

$$rp = \begin{cases} \frac{P_a}{P_{CC}} & \text{se}\ \ P_a < P_{CC} \\ \frac{P_{CC}}{P_a} & \text{se}\ \ P_a > P_{CC} \end{cases} \tag{7}$$

and:

$$rpc = \frac{2}{\gamma+1}^{\frac{\gamma}{\gamma\ 1}} \tag{8}$$

CA = product of the orifice coefficient and its equivalent area;
γ = ratio constant pressure specific heat to constant volume specific heat;
ρ_{CC} = mixture (air + halon) cargo compartment density;
P_{CC} = total cargo compartment pressure;
P_a = external atmospheric pressure;
rp = pressure ratio; and
rpc = critical pressure ratio.

Note that the mixture (air + halon) leakage mass flow rate ($\dot{m}_E$) occurs through an orifice of area A corresponding to the cargo compartment total leakage.

Assuming that halon, air and the mixture have a perfect gas behavior, the partial and total pressures can be calculated as:

$$P_H = \frac{m_H}{M_H}\frac{RT_{CC}}{V_{CC}} \tag{9}$$

$$P_{AIR} = \frac{m_{AIR}}{M_{AIR}}\frac{RT_{CC}}{V_{CC}} \tag{10}$$

$$P_{CC} = \frac{m_H}{M_H} + \frac{m_{AIR}}{M_{AIR}}\frac{RT_{CC}}{V_{CC}} \tag{11}$$

The air and halon input mass flow rate must be previously known. In an actual halon bottle discharge, these rates are function of both the bottle internal pressure and the total discharge duct pressure drop. In this work, it is assumed that the input mass airflow rates and the halon mass flow rate from each bottle are constant.

Solution methodology

The time-variation of the halon and air masses inside the aircraft cargo compartment was mathematically modeled by a first-order ordinary differential equations system, equations (1 and 2), using the lumped parameter approach. Therefore, this problem can be solved using a fourth-order Runge–Kutta numerical scheme. This algorithm is known to be very accurate and well-behaved for a wide range of problems (Fletcher, 1988). The Runge–Kutta method of numerically integrating ordinary differential equations is based on a trial step at the midpoint of an interval to allow canceling out lower-order error terms. In the present study, the needed ordinary differential equations systems were solved using the Runge–Kutta scheme available in the Mathcad tool (Mathsoft Inc, 1999).

Results and discussion

Numerical simulations of the fire suppression system were carried out using the parameters listed in Table I. It is important to observe that these used values may not match the real cargo compartment fire extinguishing device due to data publishing restrictions (confidentiality agreement). For example, proper values for the mass content of the high and low pressure bottles are 6 and 10 kg, respectively (Figure 1) for a commercial transport aircraft (Penteado, 2004).

The mass airflow rate is constant during all the fire suppressing agent release, as shown in Figure 3. After the fire alarm, the high pressure bottle is discharged, and occurring an abrupt increase in the halon mass flow rate during about 30 s, corresponding to 20 to 50 s (Figure 3). Then, the halon in the low pressure bottle is released to maintain a minimum fire extinguishing capability during the remaining flight time. The total time of the halon discharge is equal to 150 s.

Figure 4 presents the time-evolution of air, halon and mixture masses stored inside the cargo compartment. Results showed that with a constant input airflow rate (Figure 3), the stored air mass inside the cargo compartment increases when the halon injection initiates (Figure 4). The total and partial

Table I Parameters used in the numerical simulation of the fire suppression system

Parameters	Value
Cargo compartment volume	8 m^3
Cargo compartment temperature	25°C
Cargo compartment initial pressure	75 KPa
External atmospheric pressure	50 KPa
CA	0.01 m^2
γ	1.33
Air molecular mass	28.966 kg/kgmole
Halon molecular mass	148.93 kg/kgmole
Air mass flow rate	7 kg/s
Halon mass flow rate (kg/s)	0 if t < 20s 0.63 if 20 s ≤ t < 50 s 0.0125 if t ≥ 50 s

Figure 3 Air and halon mass flow rates as a function of the time

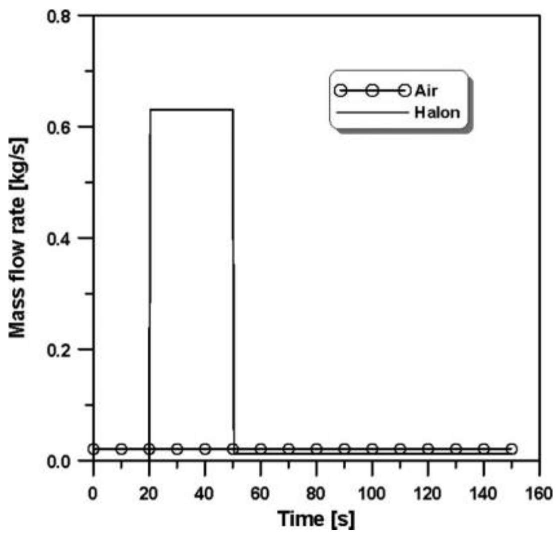
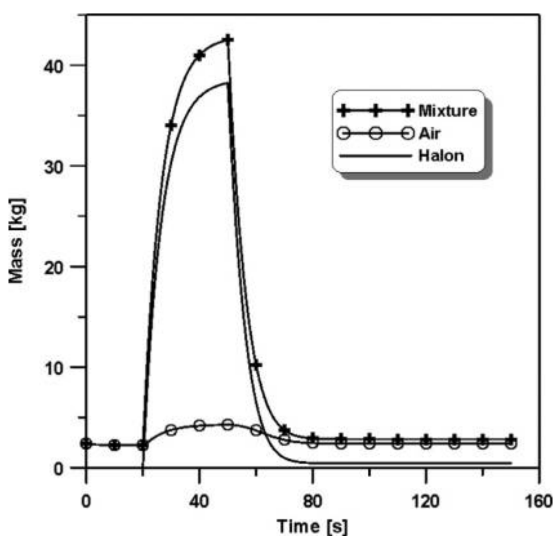


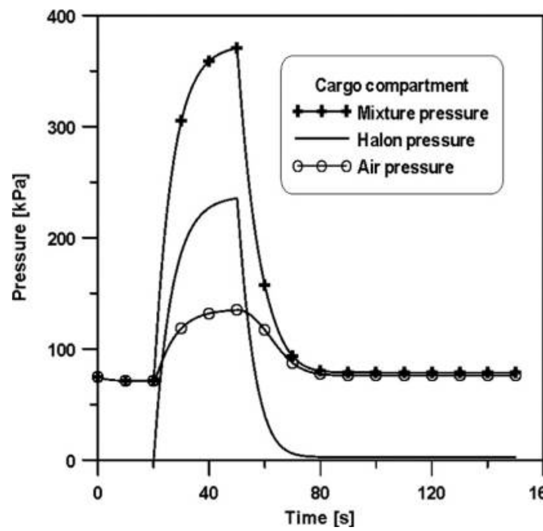
Figure 4 Cargo compartment masses as a function of the time



cargo compartment pressures time-evolution are shown in Figure 5. Before the fire detection system alarm, the total pressure is constant and equal to the air partial pressure. During these initial 20 s, the pressure differential results in an exit mass flow rate equal to the input mass airflow rate. At 20 s, the fire alarm induces the halon high pressure bottle discharge. To compensate the increase in the input mass flow rate, the exit mass flow rate should also elevate.

However, this output flow rate only increases if the pressure ratio is reduced by the increase in the internal pressure due to the larger mixture (air + halon) mass stored in the cargo compartment, as can be seen in Figures 4 and 5. When the halon discharge of the high pressure bottle stops, the halon discharge of the low pressure bottle begins during the final operation stage of the fire suppressing system. As the halon input mass flow rate decays, both the masses stored and pressures decrease. After the transient time interval, these variables assume stabilized values with the total cargo

Figure 5 Cargo compartment pressures as a function of the time



compartment pressure maintained at the level correspondent to the sum of the air and halon partial pressures.

Figure 6 shows the air and halon mass concentrations in the cargo compartment as a function of the time and the halon volumetric concentration is presented in Figure 7. These distributions are symmetrical and supplementary, that is, when the air mass concentration reaches a maximum value, the halon one assumes a minimum value. Note that the halon mass concentration increases abruptly when the halon is released from the high pressure bottle.

During the halon high discharge, its volumetric concentration reaches the high level required to the fire suppression (Figure 7). After the end of the halon high pressure bottle release, it begins the second bottle discharge. The objective of the low pressure bottle discharge is only to maintain a minimum inerting concentration. With this halon discharge, the mass and volumetric halon concentrations stabilize in a remaining value during the rest of the halon injection.

Figure 6 Air and halon mass concentration as a function of the time

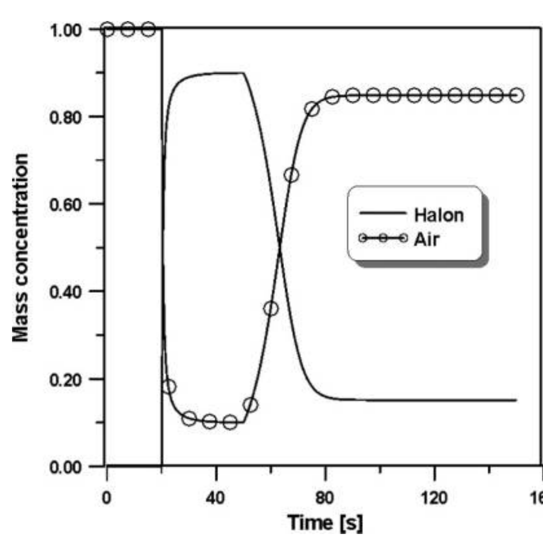
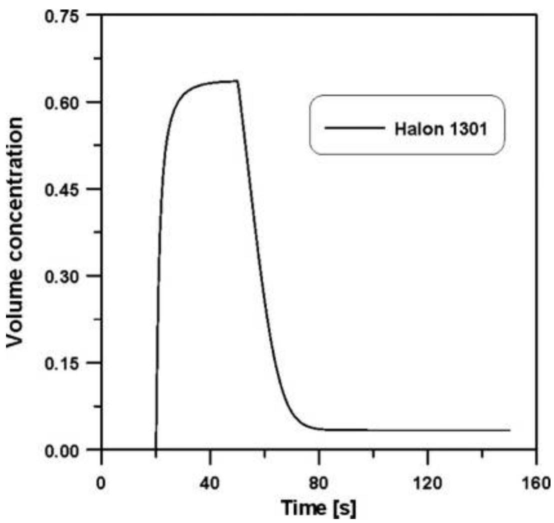


Figure 7 Volumetric concentration as a function of the time



The cargo compartment initial pressure listed in Table I simulates a pressurized zone equivalent to altitude of 8,000 ft (a typical cabin cruise flight). This simulation was also compared with experimental results of an in-flight test (Penteado, 2004) showing good agreement. However, these last results cannot be herein presented due to confidential information reasons (the present work and the experimental set-up were developed in partnership with a Brazilian aircraft manufacturer). Even not being allowed to use proper real values, the main guidelines to support a fire extinguishing system design have been provided.

Conclusion

This work focused on the numerical simulation of the injection of the fire suppressant agent (Halon 1,301) in an aircraft cargo compartment applying the lumped parameter approach. This formulation does not show spatial concentration non-uniformities but provides useful and rapid information to design the aircraft cargo compartment fire extinguishing system. The designer using this developed computational tool can calculate the main parameters required to fire suppression system design: the time to Halon concentration to achieve the fire suppressant value (maximum), the halon volumetric concentration value obtained with the high flow injection, the time to reach the inerting volumetric concentration and the inerting concentration value obtained with the discharge of the low pressure bottle. It was shown that this numerical simulation provides a reliable tool to predict the fire extinguishing agent behavior and to adjust the design parameters to satisfy certification requirements.

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Further reading

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