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NUMERICAL SIMULATION OF THE CONCENTRATION OF FIRE EXTINGUISHING AGENT IN AIRCRAFT CARGO COMPARTMENT

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Abstract. *Commercial aircrafts must have a fire suppression system in the cargo compartment to satisfy the safety and certification requirements. These fire extinguishing systems are based on a gas discharge that performs a physicochemical inhibition of the combustion reaction. Most system uses halon 1301 as the fire extinguishing agent which is stored in liquid phase within one or two bottles. As the fire is detected, the fire suppressant agent is discharged in the cargo compartment with a Halon volumetric concentration higher than 5 % for fire knockdown in the initial stage. In the next stage, the halon volumetric concentration should be maintained above the inerting level (3 %). At this work, the mathematical model of the halon volumetric concentration was obtained applying the lumped parameter approach and the differential equation system is solved using a fourth-order Runge-Kutta scheme. This methodology allows determining the transient behavior of the following parameters: halon volumetric concentration, halon and air masses and the cargo compartment pressure. This numerical simulation provides a reliable tool to predict the fire extinguishing system behavior and to adjust the design parameters to satisfy the certification requirements.*

Keywords. *fire suppression, cargo compartment, fire extinguisher, halon 1301, aircraft safety.*

1. Introduction

Cargo compartments in large transport aircraft present a potentially severe fire problems because of the large quantity and great variety of combustible materials carried in passenger luggage, mail, and cargo, including hazardous materials. 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 wall liners and fire detection and suppression systems. The purposes of these design features 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).

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. Iodine can be used but it is significantly more expensive with no advantage over the others, Lombardo (1993). 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 halocarbon suppressant agents as halon 1301 (NFPA, 1997) has been used in the fire suppression system. Halon 1301 (bromotrifluoromethane or CF_3Br) is a colorless, odorless, electrically nonconductive gas that is an effective medium for extinguishing fires with an acceptable toxicity level. An excellent fire extinguishing agent (gas) currently installed in thousands of locations throughout the world protecting sensitive electronic equipment, typically found in computer rooms, telecommunications centers, data processing environments and aviation.

1.1 Historical notes

The fact that Halon 1301 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 1301 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 since 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 1301. Today 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 1301 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:

(i) the production and use of halon 1301 was banned for developed countries from January 1st, 1994 onwards;

(ii) the production and use of halon 1301 is to be banned for developing countries from January 1st, 2010 onwards;

(iii) the import and export of halon is strongly restricted.

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. To form a security stock of halon 1301 for essential uses, some industrial countries have build-up so-called halon banks. The idea is all halon 1301 which was part of decommissioned installations is collected, declared and stored under controlled conditions. Depending of the national policies halon can be brought for storage in a halon bank free of charge or on a clear defined cost basis. In most cases such halon banks are controlled and supervised directly by the government or by the national trade organization.

The Montreal Protocol not only banned halon 1301 and brought alternatives to the market, but also made customers more aware of fire suppression systems. Finally, the Montreal Protocol also induced a complete change to the market for automatic extinguishing systems since alternatives to halon 1301 have to be found. Since the signing of the Montreal Protocol extensive efforts has been devoted to the search for halon alternative to replace halon 1301 (Yang et al., 1996). Several hydrofluorcarbons (HFC) and perfluorcarbons (FC) have been developed as candidate halon replacements (Saso et al., 1996).

1.2 Halon based fire suppression system

Typically, aircraft cargo compartments are classified in A, B, C and D classes. Class A represents compartments where the fire is detected by any crew members and is easily accessible during the flight. They are used to put objects (named stowages). Class B compartments possess a smoke detection system and are also accessible by the crew as in the Class A case.

According to the aviation regulations a Class C cargo compartment is one in which:

(1) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

(2) There is an approved built-in fire extinguishing system controllable from the pilot or flight engineer stations;

(3) There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers;

(4) There are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

The class D compartments, which are minimally, ventilated cargo holds have been used in smaller commercial airplanes that fly short to medium routes. These compartments contain primarily passenger luggage and present a low ignition hazard. Reduced oxygen at cruising altitudes further lowers the likelihood of sustained combustion in the cargo compartment.

However, with the growth of air cargo transportation as a revenue source, the mix of items and materials carried in cargo compartments has changed. Commercial products, industrial materials, and airplane components en route to airline maintenance stations have joined baggage below the passenger cabin. Though the compartments are designed and required to be free of ignition sources, the risk that a sequence of events involving human error could lead to a fire is perceived to have increased.

Basically, a Class C cargo compartment is in excess of 1000 cubic feet in volume and requires a built-in detection and extinguishing system with the agent discharge being controlled from the flight deck. Class D cargo compartments are less than 1000 cubic feet in volume, with prescribed allowable air leakage rates, and contain a fire by oxygen starvation.

Currently, cargo compartments in large transport aircraft satisfy the provisions of either Class C or Class D compartments. Both compartment classes require burn through-resistant cargo liners. The primary distinction lies in whether a detection and suppression system is also required.

The fire suppression system of the cargo compartment consist of an initial discharge of a fixed quantity of agent followed by a metered system that added agent to maintain a minimum concentration, Fig. (1). This system is composed by two bottles: high (1) and low (2) pressures recipients, Fig. (1). The quantities for the initial discharge and the subsequent minimum design concentration that were maintained were based on the current industry practice: (a) 5% initial concentration of halon 1301 in an empty cargo compartment volume to suppress any combustion to controllable levels and (b) 3% concentration for the duration of the flight to prevent reignition or spreading of the combustion.

For airplanes certified for extended-range twin-engine operations (ETOPS), the fire-suppression system must be able to sustain a 3 % 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.

The system shown in Fig. (1) comprises two fire extinguishers bottles (low and high pressure) is located in the middle avionics compartment that are equipped with dual outlets to discharge suppression agent into either of the cargo compartments. Each bottle includes a pressure switch for sensing and reporting extinguisher vessel pressurization, and two initiators for opening the agent outlets. The initiators are electro-explosive devices that rupture an outlet in the bottle when fired. The suppression agent is expelled through the extinguishing lines to nozzles in either the forward or aft cargo compartment. There are two nozzles each located in forward and aft ward cargo compartments.

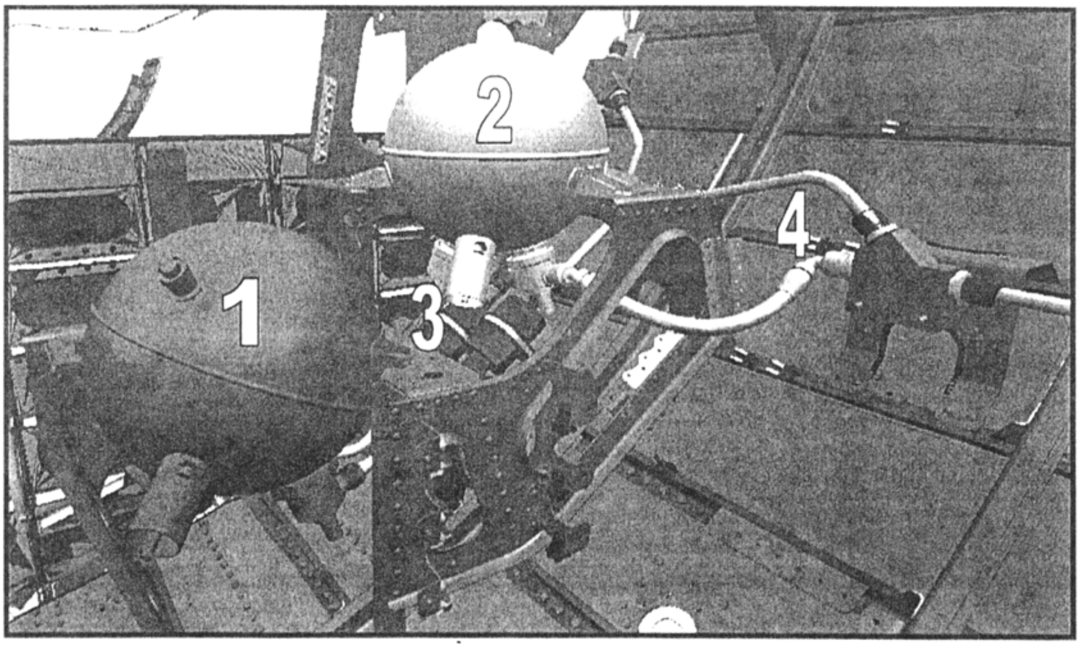

Figure 1 – Fire suppression system location in an aircraft cargo compartment: 1) Low pressure bottle; 2) High pressure bottle; 3) DMU (Drier Metering Unit) e 4) Tee type connector.

The design of the high rate discharge extinguisher allows for rapid discharge of the suppression agent to provide an immediate knockdown concentration to extinguish the fire. The low rate discharge extinguisher discharges through the DMU (Drier Metering Unit) that provides reduction of the agent flow rate and prevents moisture from forming at the restricted orifice. The agent from the low pressure bottle will maintain a inerting concentration in the compartment for 60 minutes to allow the crew to land the aircraft with safety. The high pressure bottle will supply a high initial halon mass flow rate to suppress the fire. After this rapid discharge, it will begin the lower halon mass flow rate of the low pressure bottle necessary to satisfy the minimum halon volumetric concentration requirement to maintain the inerting concentration.

At this context, the objective of the present work is to simulate the fire suppressant agent injection inside the aircraft cargo compartment using a lumped parameter approach. This study will allow determining the halon volumetric concentration time-evolution and also to verify if the certification requirements will be satisfied.

2 MATHEMATICAL FORMULATION

The aircraft cargo compartment is represented by a simplified control-volume model shown in Fig. (2). Halon and air masses time-variation are mathematically modeled by the differential equation system represented by Eqs. (1) and (2). This system was obtained applying the mass conservation law with a lumped parameter approach.

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

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

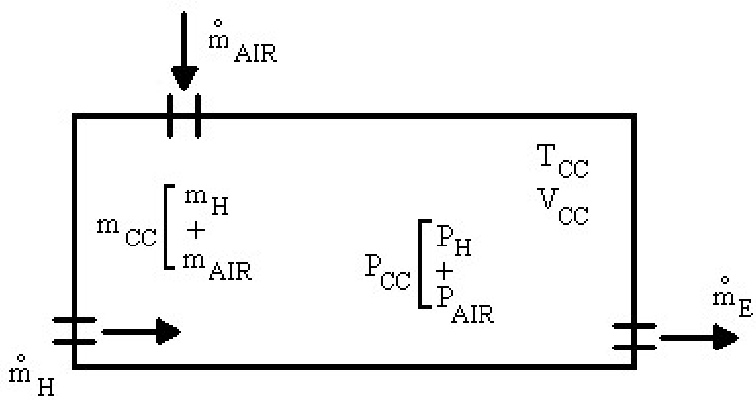

Figure 2 – A based control-volume model for the air-halon mixture flow inside the aircraft cargo compartment.

with:

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

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

where:

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

The mixture (air + halon) exit mass flow rate, present in Eqs.(1) and (2), is calculated by:

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

or

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

where:

$$rp = \begin{cases} \dfrac{P_a}{P_{CC}} & se \;\; P_a < P_{CC} \\ \dfrac{P_{CC}}{P_a} & se \;\; P_a > P_{CC} \end{cases} \quad \text{and } \; rpc = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

with:

CA	product of the orifice coefficient and the equivalent surface
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
rpc	critical pressure ratio

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

$$P_H = \left(\frac{m_H}{M_H}\right)\left(\frac{RT_{CC}}{V_{CC}}\right) \tag{6}$$

$$P_{AIR} = \left(\frac{m_{AIR}}{M_{AIR}}\right)\left(\frac{RT_{CC}}{V_{CC}}\right) \tag{7}$$

$$P_{CC} = \left(\frac{m_H}{M_H} + \frac{m_{AIR}}{M_{AIR}}\right)\left(\frac{RT_{CC}}{V_{CC}}\right) \tag{8}$$

where:

P_H	Halon partial pressure
P_{AIR}	Air partial pressure
V_{CC}	Free cargo compartment volume
T_{CC}	Cargo compartment temperature
M_H	Halon molecular mass
M_{AIR}	Air molecular mass
R	Universal gas constant

To the mathematical formulation above proposed, the air and halon input mass flow rate must be 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.

3 SOLUTION METHODOLOGY

The time-variation of the halon and air masses in the aircraft cargo compartment is mathematically modeled by a first-order ordinary differential equations system, Eqs. (1) and (2), using the lumped parameter approach. In the present study, this problem is solved using a fourth-order Runge-Kutta numerical scheme. This 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. Considering a single variable problem this algorithm takes the form:

$$\frac{dy}{dt} = f(t, y) \tag{9}$$

with initial condition $y(0) = y_0$. Suppose that x_n is the value of the variable at time t_n. The Runge-Kutta formula takes x_n and t_n and calculates an approximation for x_{n+1} at a brief time later, t_{n+h}. It uses a weighted average of approximated values of $f(t, x)$ at several times within the interval (t_n, t_{n+h}). The method is given by:

$$x_{n+1} = x_n + \left(\frac{h}{6}\right)(k_1 + 2k_2 + 2k_3 + k_4) \tag{10}$$

where:

$$k_1 = f(t_n, x_n)\ ;\ k_2 = f\left[t_{n+\frac{1}{2}}, x_n + \left(\frac{h}{2}\right)k_1\right]\ ;\ k_3 = f\left[t_{n+\frac{1}{2}}, x_n + \left(\frac{h}{2}\right)k_2\right] \text{ and } k_4 = f\left(t_n, x_n + hk_3\right)$$

To run the simulation, we simply start with x_0 and find x_1 using the algorithm above. Then we plug in x_1 to find x_2 and so on. The Runge-Kutta algorithm is known to be very accurate and well-behaved for a wide range of problems (Fletcher, 1988).

5 RESULTS

The numerical simulations were carried out utilizing the program implemented in MathCad®2000 (1999). This software is a computational-mathematical tool and presents an easily graphical user interface. To solve the differential equation system, Eqs. (1) and (2), using the fourth-order Runge-Kutta method, some parameter were maintained constants and are listed in Tab. (1). The air and halon input mass flow rates are also presented in Fig. (3).

Table 1 – Constant parameters used in the numerical simulations.

Parameters	Value
Cargo compartment volume	$20m^3$
Cargo compartment temperature	$25°C$
Cargo compartment initial pressure	$101.325kPa$
Air initial mass	$23.679kg$
External atmospheric pressure	$50kPa$
CA	$1m^2$
γ	1.33
Air molecular mass	$28.966\ kg\ /\ kgmole$
Halon molecular mass	$148.93\ kg\ /\ kgmole$
Air mass flow rate	$7kg\,/\,s$
Halon mass flow rate *(kg/s)*	$0\quad if\ \ t < 20\ s$ $63\quad if\ \ 20\ s \le t < 50\,s$ $1.25\ \ if\ \ t \ge 50\ s$

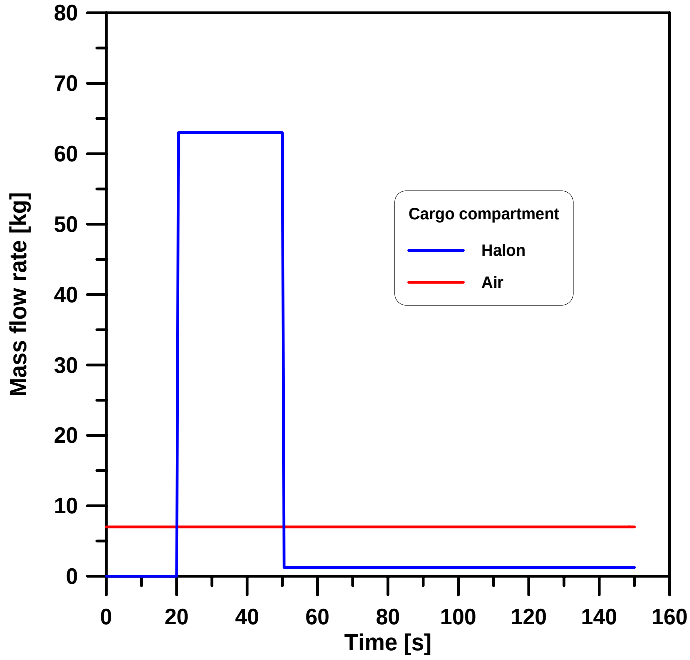

Figure 3 – Air and halon mass flow rates as a function of the time.

The mass airflow rate is constant during all the fire suppressing agent injection. After the fire alarm, the high pressure bottle is discharged, and occurring an abrupt increase in the halon mass flow rate during about 30 seconds. Then, the halon in the low pressure bottle is released to maintain a minimum fire extinguishing capability during the remaining flight time as shown in Fig. (3). Results showed that with a constant input airflow rate, Fig. (3), the stored air mass, Fig. (4), inside the cargo compartment increases when there is halon injection.

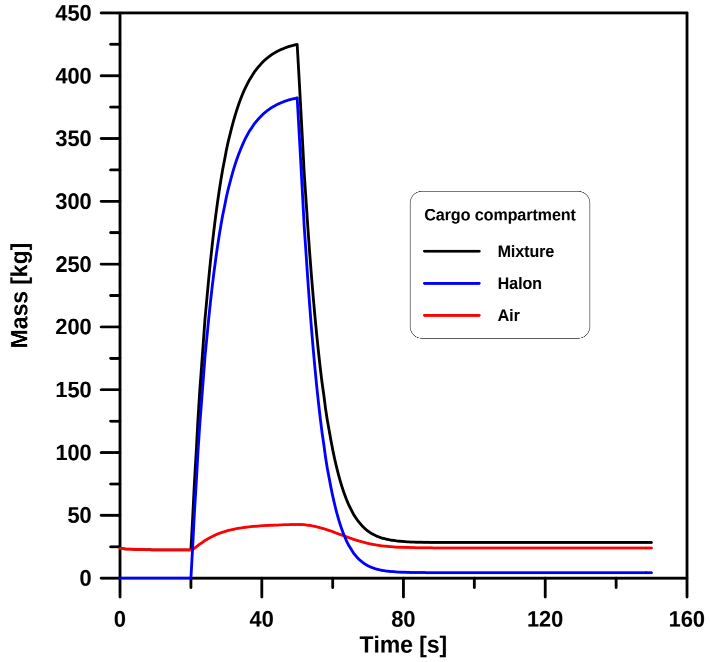

Figure 4 – Cargo compartment masses as a function of the time.

Figure (4) presents the time-evolution of the air, halon and mixture masses stored inside the cargo compartment. In Fig. (5), the total and partial cargo compartment pressures are illustrated. Before the fire detection system alarm, the total pressure is constant and equal to the air partial pressure. During these initial 20 seconds, the pressure differential results in an exit mass flow rate equal to the input mass airflow rate. At 20 seconds, 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 increases.

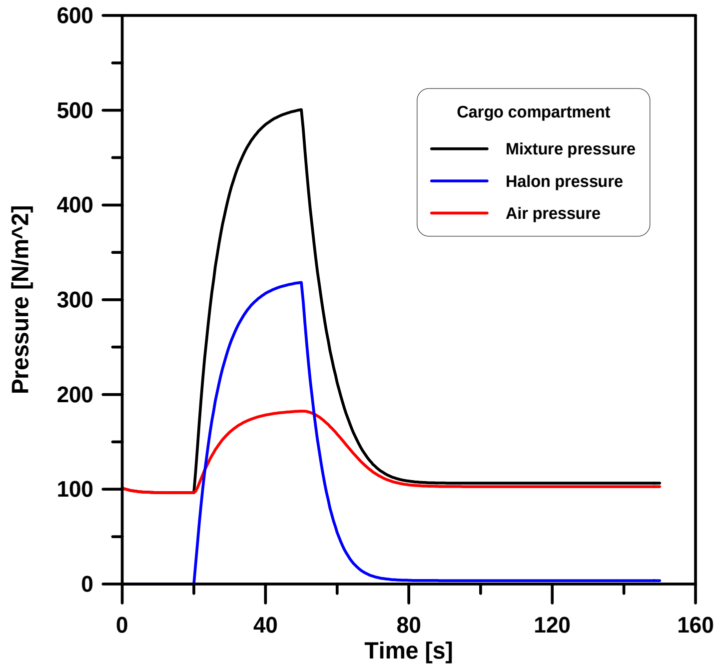

Figure 5 – Cargo compartment pressures as a function of the time.

However, this output flow rate only elevates 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 show in Fig. (4) and Fig. (5). When the halon discharge of the high pressure bottle stops, it begins the halon discharge of the low pressure bottle 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 as presented in Fig. (4) and Fig. (5), respectively. After the transient time interval, these variables assume stabilized values with the total cargo 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. The halon volumetric concentration is presented in Fig. (7).

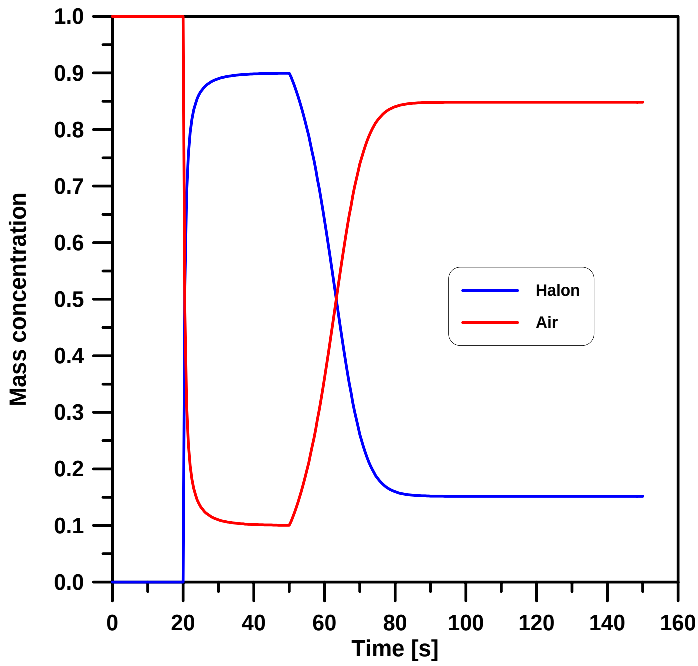

Figure 6 – Air and halon mass concentrations as a function of the time.

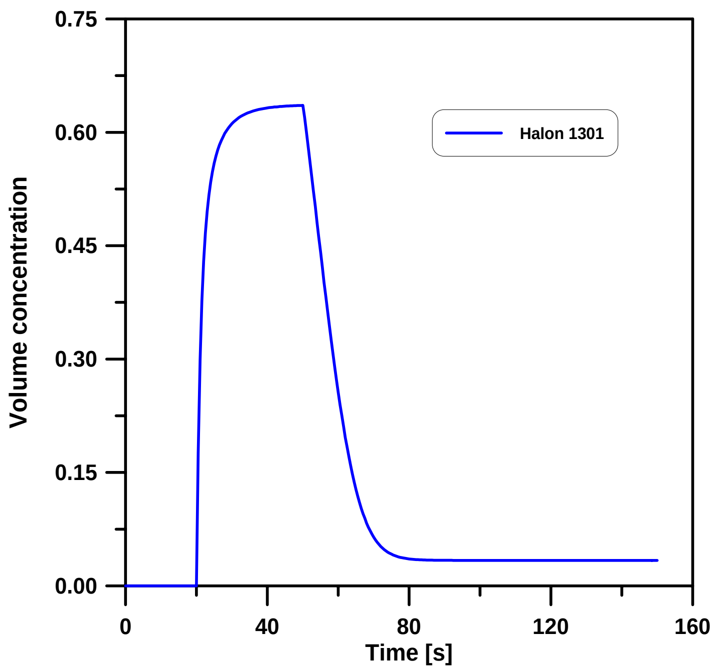

Figure 7 – Halon volumetric concentration as a function of the time.

These distributions are symmetrical and supplementary, that is, when the air mass concentration reaches a maximum value, the halon one assumes a minimum value. 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, Fig. (7).

After the end of the discharge of the halon high pressure bottle, 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.

6 FINAL COMENTS

This work focused on the numerical simulation of the injection of the fire suppressant agent (halon 1301) in an aircraft cargo compartment applying the lumped parameter approach. This formulation does not show concentration spatial non-uniformities but provide useful and rapid information to design the aircraft cargo compartment fire extinguishing system.

The designer using this developed computational tool can to calculate the main parameters necessary to dimension this system: the time to halon concentration reach 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 system behavior and to adjust the design parameters to satisfy the certification requirements.

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