Concentration analysis of extinguishing agents and toxic gases in small cabin aircraft

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Abstract. *The objective of this work was to develop a methodology and a tool to analyze volumetric concentration over time of toxic gases inside small aircraft cabins during a fire event. These gases could be generated by the combustion or by extinguishing agents used to put out the fire. A mathematical model was developed using the perfect stirrer approach since it has been demonstrated by tests to give very similar data to the real results and this is what is suggested and accepted by the authorities. The inputs of the problem are the mass flow of the extinguishing agent and other toxic gases that could be generated by the combustion, the variation of the cabin altitude and the variation of the cabin air inflow. The outputs are the volumetric concentration of all gases inside the cabin over the time. The contribution of this tool is in the preliminary definition of the cabin fire extinguishers and the visualization of the effects of possible cabin altitude and air inflow changes during a fire event. This tool will also be useful in the study of replacements of existing extinguishing agents by others least toxic as well as the reevaluation of the existing fire extinguisher installations with the possible change at the toxicity levels recommended by the authorities. Even though the results generated by the tool are conservative, they were demonstrated to be consistent for a simulation case of permanent regime, for a case of inflow of more than one gas with the aircraft in cruise and constant altitude, and with the change in cabin altitude.*

Keywords 1.Extinguishing agent concentration analysis. 2. Fire supression system. 3. MatLab/Runge Kutta

1. INTRODUCTION

The occurrence of smoke or fire aboard aircraft presents a potential situation of risk, aggravated by the large amount of highly flammable fuel carried and the limited passenger evacuation possibilities. Substantial improvement has been made on the flammability requirements on the materials used inside the cabin, cabin evacuation has become more efficient and the fire fighting on ground has become better. However, recent data indicates that the probability of passengers experiencing an event of smoke in flight is very high.

For many years, small civil aircraft were not required to carry portable fire extinguishers inside the cabin. Only large aircraft certified under Part 25 should be equipped with an approved fire extinguisher. In 1987, through NPRM 83-17, Part 23 required portable fire extinguishers for commuter category aircraft.

Small aircraft under the commuter category present the agravant of not having to carry a crew member inside the cabin. This fact can result in a longer time for reaction of a cockpit flight crew to extinguish a possible fire in the cabin or a regular passenger with no training trying to do so. For this reason, aircraft manufactures and operators need to be more careful not only in the choice of the type of the extinguisher, but also on its location on the cabin, choosing readily accessible places and if necessary using placards in order to minimize the reaction time in an event of fire.

The most common type of extinguishing agent used in aviation is Halon due to its effectiveness and the low residue left after being used. The trouble with Halon is that it is an ozone-depleting substance, harmful to the Earth's stratospheric ozone layer and also can become toxic in high concentrations. This last issue is potentialized in a small aircraft where the cabin volume and air ventilation are limited.

The motivation of this work was the fact that the existing recommendations for the choice of fire extinguishing agents do not take into consideration some important variables and the fact that new agents are being offered, resulting in changes in acceptable toxicity levels. The purpose of this work was to develop a simple tool capable of generating more realistic information about the concentration of extinguishing agents inside the cabin, including cabin altitude variation over time, simulating the use of forced outflow of air out of the cabin by the pilot or, if provided by the aircraft design, the increase on the air inflow inside the cabin. This tool can help in the preliminary selection of extinguishing agents and their quantities, in the evaluation of existing installations and in other fire studies inside the cabin such as the evaluation of the concentration of gases that are sub products of the combustion of materials.

2. EXTINGUISHING AGENTS CONCENTRATION RECOMENDATIONS

FAA Advisory circular 20-42C, Hand Fire Extinguishers For Use In Aircraft, presents the recommendations for the safe use of Halon 1211, Halon 1301 and Carbon Dioxide fire extinguishers onboard aircrafts.

The minimum confined volume space recommended by AC 20-42C is 312 cubic feet for the standard 2.5 pounds Halon 1211 used onboard aircraft and 132 cubic feet for the Halon 1301, These volumes were determined before the cardiotoxic test became the standard for industries in general. The volume for Halon 1211 is based in a volumetric concentration allowed of 2% maximum where the rate of air change inside the cabin is unknown.

For aircraft where the exchange air time is known, the recommendations are 4%.min for Halon 1211 and 10%.min for Halon 1301. This means that a volumetric concentration of 4% of Halon 1211 can be kept during a period of 1 minute without causing any harm to the occupants. The minimum safe compartment volumes are calculated using the perfect stirrer approach, in which the compartment volume and the air exchange time are used to obtain the maximum amount of agent that can be used.

The perfect stirrer approach assumes that all extinguishing agent discharged immediately mixes homogeneously with the air. In addition, the new air injected at the cabin mixes with the existing gas mixture decreasing the concentration of the agent over time while the mixture is ventilated out the cabin.

The calculations on AC 20-42C assume a cabin pressure based on an altitude of 8000 feet and a temperature of 70 ^{o}F. In addition, the calculations assume that the extinguisher is discharged instantaneously. Based on the current recommendations, an aircraft with a ventilation rate of one air exchange per minute would need to have a cabin volume of 197,5 cubic feet in order to be able to use a 2.5 pounds Halon 1211 safely.

AC 20-42C was last revised in the 80's. Since new agents are being developed to replace Halon 1211 which is an ozone depleting substance, a committee was created to update this circular. Several discussions were made by this group regarding the appropriate methodology that should be used to determine the minimum volume of the required compartment for the safe use of Halon 1211 and its substitutes onboard aircraft. A possible approach would be to use the PBPK (Physiologically Based PharmocoKinetic) method to provide a first approach.

When air containing a halocarbon agent is inhaled, part of the halocarbon is introduced in the blood stream through the lungs. The concentration of the halocarbon dissolved in the blood is related to the concentration in the air inhaled and the exposing time. If the exposing time is high enough, the heart can be sensitized to adrenalin. In the presence of a high level of adrenalin, the heart can experience arrhythmia. The PBPK methodology considers this dynamic and was implemented in this work.

3. MATHEMATICAL MODEL

In order to obtain the mathematical equations that represents the discharge of extinguishing agents or toxic gas generation resulted by the combustion of materials inside an aircraft cabin , the control volume represented by Fig. 1 can be used:

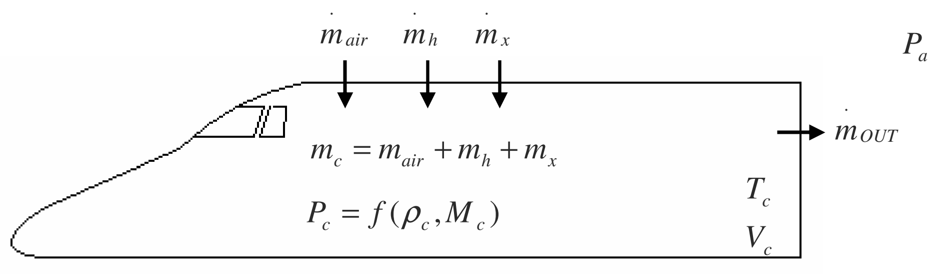

Figure 1. Control volume used

Where:

m_{air} – Air mass accumulated inside the cabin

m_h – Halon mass accumulated inside the cabin

m_x – Additional gas mass accumulated inside the cabin

m_c – Combination of the masses accumulated inside the cabin

$\dot{m}_{air}$ – Air inflow

$\dot{m}_{h}$ – Halon inflow

$\dot{m}_{x}$ – Additional gas inflow

$\dot{m}_{out}$ – Mixture outflow (air + halon + x)

P_a – External Pressure

P_c – Cabin Pressure (combined partial pressures)

ρ_c – Mixture density
M_c – Molecular mass of the mixture
V_c – Total cabin Volume
T_c – Cabin temperature

The differential equations of the mass variation of each component over time can be obtained by the mass conservation principle and the perfect stirrer approach in which all components of the controlled volume are homogeneously distributed in every part of the cabin:

$$\frac{dm_c}{dt} = \dot{m}_{air} + \dot{m}_h + \dot{m}_x - \dot{m}_{out} \tag{1}$$

$$\frac{dm_{air}}{dt} = \dot{m}_{air} - \dot{m}_{out}\frac{m_{air}}{m_c} \tag{2}$$

$$\frac{dm_h}{dt} = \dot{m}_h - \dot{m}_{out}\frac{m_h}{m_c} \tag{3}$$

$$\frac{dm_x}{dt} = \dot{m}_x - \dot{m}_{out}\frac{m_x}{m_c} \tag{4}$$

As described by (Zaparoli, E.L; KUROKAWA, F.Y.; ANDRADE, C.R, 2004), the mass flow rate leaving the cabin can be determined by the following equations:

$$\dot{m}_{out} = CA\sqrt{2\frac{\gamma}{\gamma-1}\rho_c P_c\left[(rp)^{\frac{2}{\gamma}} - (rp)^{\frac{\gamma+1}{\gamma}}\right]} \qquad \text{if} \qquad rpc \le rp \le 1 \tag{5}$$

or

$$\dot{m}_{out} = CA\sqrt{\rho_c P_c \gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad \text{if} \qquad rp < rpc \tag{6}$$

Where:

$$rp = \begin{cases} \dfrac{P_a}{P_c} & if \quad P_a < P_c \\ \dfrac{P_c}{P_a} & if \quad P_a > P_c \end{cases}$$

C – Orifice coefficient
A – Equivalent leaking area
γ – Relation between specific heat in constant pressure and constant volume
ρ_c – Density of the mixture of gases
P_c – Total pressure in the cabin
P_a – External atmospheric pressure
rp – Pressure relation
rpc – Critical pressure relation

The cabin pressure is obtained by the equation below:

$$P_c V_c = \frac{m_c}{M_c} R T_c \tag{7}$$

Where:

$$M_c = \frac{m_c}{\frac{m_h}{M_h} + \frac{m_{air}}{M_{air}} + \frac{m_x}{M_x}} \tag{8}$$

4. SOLUTION METHODOLOGY

In order to obtain the gases concentrations over time, computational tools can be used. In this particular work, Matlab was used to solve the ordinary system of differential equations represented by equations (1), (2), (3) and (4). The fourth order Runge Kutta method was used using the fluxogram represented by Fig. 2.

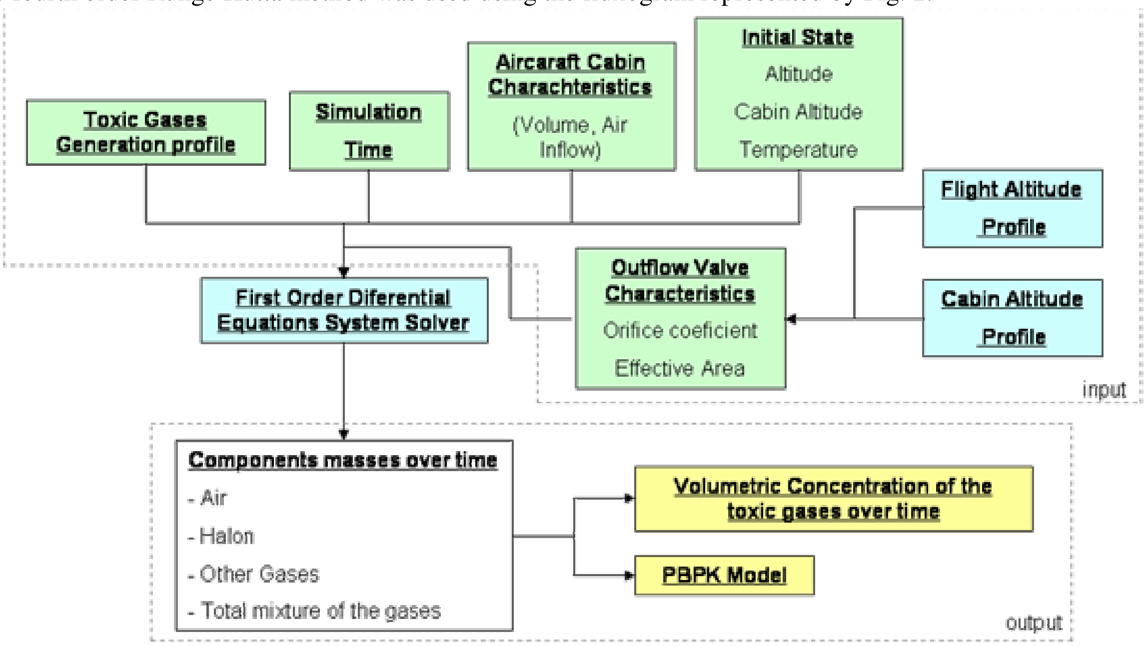

Figure 2 – Solver Fluxogram

5. RESULTS

Simulations were carried representing an aircraft with a cabin volume of 10.2 cubic meters, kept in a temperature of 24°C, initial cabin altitude of 6700 feet and flying at cruise at 41000 feet. Initially, the only existing mass inside the cabin is the air. In other words the total mass of the compartment is the air mass. Two other gases were introduced, one being Halon 1211 and the other a fictitious one that was called "X" representing a compound resulted by the combustion or a second extinguishing agent.

The first simulated case represents a fire situation where a 2.5 pounds Halon 1211 bottle would be enough to extinguish it and the resulting gases from combustion could be ignored. In addition, having the fire extinguished and the risk situation controlled, the pilot would not perform any descend maneuver. The simulation was run during 1000 seconds with the fire extinguisher being discharged at the instant 50 seconds. Table 1 shows the input data used.

Table 1 – Input data for first simulation

Variable	Value
Total simulation time	1500 s
Temperature inside the cabin	297 K
Discharge time for Halon 1211	8 s
Discharged Halon 1211 mass	2.5 lb

Cabin Volume	10.2 m^3
Initial flight altitude	41000 feet
Molecular mass of Halon 1211	165.38 kg/mol
Molecular mass of air	28.97 kg/mol
Universal constant of gas	8314.3 kg/mol
Gravity acceleration	9.8 m/s^2
Relation between specific heat of constant pressure and volume	1.33
Absorption coefficient rate of Halon 1211	38.6
Elimination coefficient rate for Halon 1211	1.74
Area coefficient	0.01
Leak area for the outflow valve	0.0856 m^2
Time instant for the discharge of Halon	0 s

Figure 3 shows the Halon 1211 concentration increase starting at 0 seconds. Eight seconds after the discharge, which is the period of time that the extinguisher was used in this example, the Halon concentration decreases until it reaches null levels.

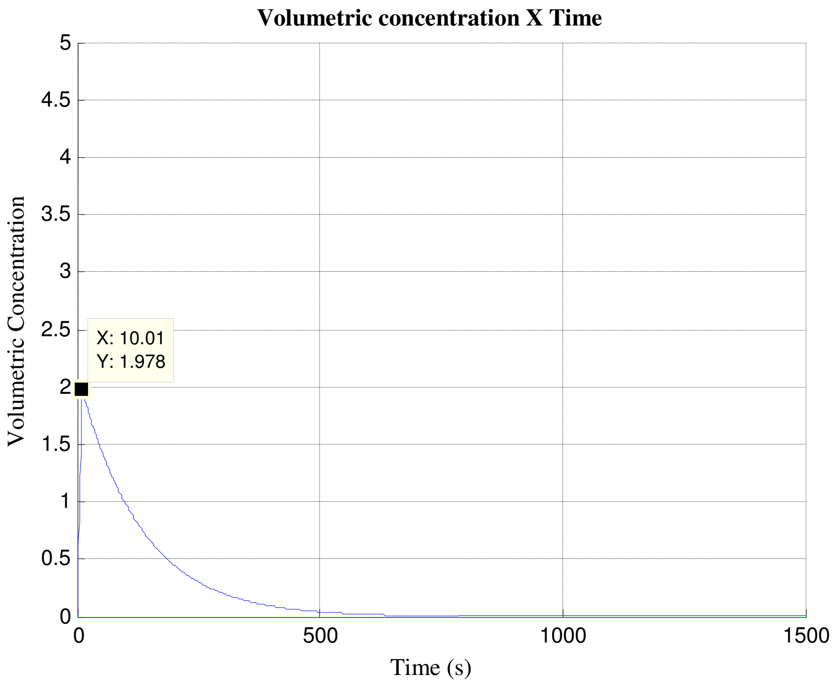

Figure 3 – Halon 1211 concentration over time

If the area under the curve is determined, the value "Volumetric Concentration x Time" as referred in AC 20-42C can be determined. For this simulation, the value was 4.38 %.min. For this simulation, the value was 4.38 %.min found by using the trapezoidal method. If the maximum allowed concentration of 4%.min of Halon 1211 is considered as recommended by AC 20-42C and considering that the calculated concentration is valid for all points of the cabin, it can be concluded that the extinguisher considered could not be used with the risk of resulting in health issues to the aircraft occupants.

The PBPK method was also applied for this simulation resulting in a peak blood concentration of twice the allowed by the recommendations which is 21mg/l.

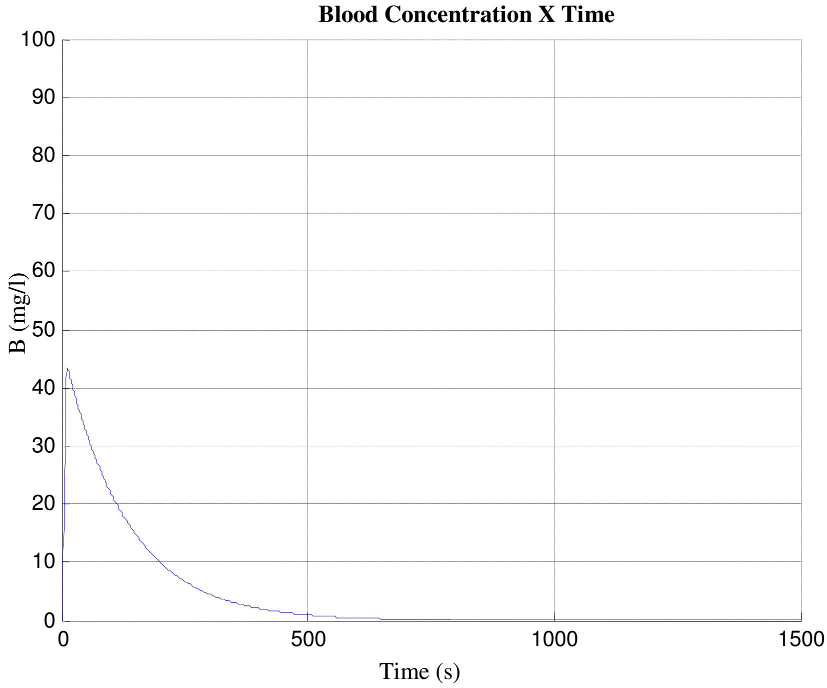

Figure 4 – Halon 1211 concentration on the blood stream

If a similar case is run with a cabin altitude change, the concentration can achieve acceptable levels. This would represent the use of the aircraft function "dump" where the outflow valve is open and the cabin altitude is increased. The inputs of this simulation and the concentration results are presented in Tab. 2 and Fig. 5 respectively.

Table 2 – Input data for second simulation

Variable	Value
Total simulation time	1500 s
Temperature inside the cabin	297 K
Discharge time for Halon 1211	10 s
Discharged Halon 1211 mass	2.5 lb
Cabin Volume	10.2 m^3
Molecular mass of Halon 1211	148.30 kg/mol
Molecular mass of air	28.97 kg/mol
Universal constant of gas	8314.3 kg/mol
Gravity acceleration	9.8 m/s^2
Relation between specific heat of constant pressure and volume	1.33
Area coefficient	0.1
Flight altitude. A descent was simulated 10 seconds after the discharge of the Halon 1211. The descent rate was 3000 feet/min. The aircraft stabilizes at 10000 feet.	41000-(50(T-20))
Leak area for the outflow valve. The outflow controls the cabin pressure for a cabin altitude increase of 2000 ft/min up to 10000 feet.	Function

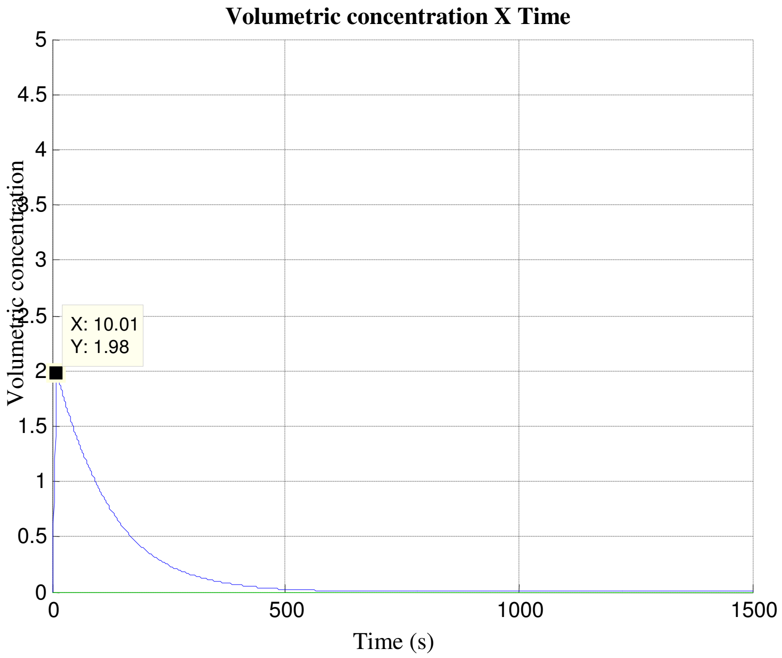

Figure 5 – Halon 1211 concentration over time

Even though the rate of cabin altitude climb is limited in order to preserve the human health, the result of this procedure is the faster evacuation of toxic gases from the cabin. The concentration on this simulation is 4%.min which is the limit accepted level for AC 20-42C. This kind of procedure is recommended by AC 20-42C but there is no calculation method presented.

A third case was simulated to represent the discharge of two gases. One being the extinguishing agent and the other a gas resulted by the combustion. Table 3 presents the input data for this case.

Table 2 – Input data for third simulation

Variable	Value
Total simulation time	1000 s
Temperature inside the cabin	297 K
Discharge time for Halon 1211	8 s
Discharged Halon 1211 mass	2.5 lb
Discharge time for X	5
Discharged X mass	1 lb
Cabin Volume	10.2 m^3
Initial flight altitude	41000 pés
Molecular mass of Halon 1211	165.38 kg/mol
Molecular mass of air	28.97 kg/mol
Molecular mass of X	35.00 kg/mol
Universal constant of gas	8314.3 kg/mol
Gravity acceleration	9.8 m/s^2
Relation between specific heat of constant pressure and volume	1.33
Area coefficient	0.1
Leak area for the outflow valve	0.0042 m^2

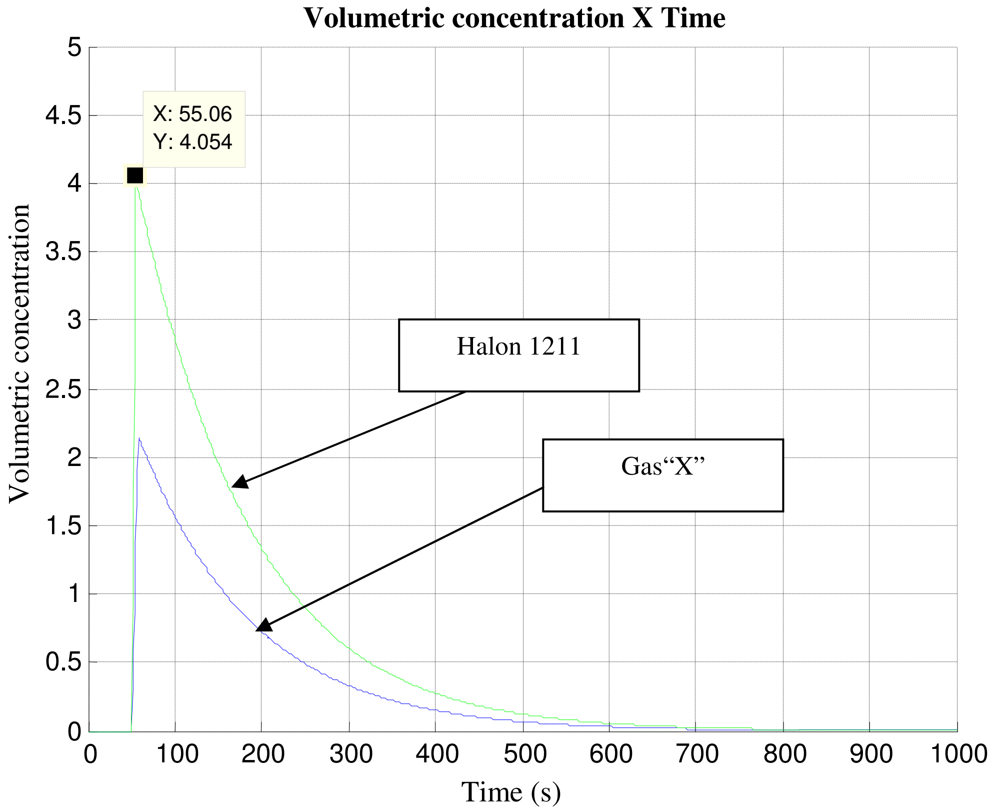

Figure 6 – Volumetric concentration over time for the discharge of Halon and the gas represented by “X”

The same method can be used to simulate as many gases as necessary, just by adding basic data and similar differential equations to the other gases presented.

5. CONCLUSION

In this work, it was possible to create a tool using the perfect stirrer approach to analyze the consequence of discharging extinguishing agents inside an aircraft cabin. Even though the results are conservative, these were shown to be more realistic then the ones presented in the current recommendations. In addition, the methodology allows more flexibility on the inputs reflecting the evolution on the technology of controlling the cabin altitude that affects directly the concentration analysis.

The tool allows that the effect of maneuvers performed be analyzed in the sense of decreasing the concentration of toxic gases inside the cabin. Based on the simulation, the increase on the outflow by decreasing the cabin pressure can help decreasing the toxic gas concentration, but not in a significant way.

The methodology presented can be very useful in the pre evaluation of fire extinguisher installation in aircraft cabins.

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