Computational Analysis of Aircraft Cargo Compartment Pressurization and Extinguishing Agent Hold Time

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Abstract

Recent studies have greatly increased understanding of the conditions present during the discharge of halon replacement fire suppressants in protected enclosures. What is not well understood, however, are the transient conditions present in an aircraft cargo hold upon discharge of halocarbon clean extinguishing agent systems into the protected space. From the recent testing, halocarbon clean agents have been shown to experience a negative pressure load from evaporative cooling early in the discharge, which becomes a positive pressure load as the agent fills the enclosure. Other variables include the characteristics of airflow to the outside as well as the extent of positive and negative pressure venting with the rest of the aircraft, both mechanical as well as emergency relief. This paper proposes a one-zone model for a typical aircraft cargo compartment in an attempt to characterize the conditions in a real cargo hold and to determine how the space would react to an agent discharge. Comparison with actual system discharge is planned.

Introduction

Modeling efforts have been undertaken for halon replacement technologies, such as halocarbon clean extinguishing agents, water mist sprays, and inert gasses, ranging in complexity, from comprehensive computational fluid dynamics models to one- and two-zone models, and focus from extinguishment models to hold time and agent distribution models [1, 3, 10, 11]. These models have helped characterize the discharge and hold times for these technologies in a growing number of applications where halon was used. One such application is in aircraft cargo holds, where halon remains the dominant fire suppressant.

Existing models, however, describe the agent discharge, retention, and distribution in empty enclosures at ground level and cannot accurately describe the conditions in an aircraft cargo compartment. Even those focusing on aircraft cargo compartments are considering only empty cargo compartments [11]. In reality the cargo loading and pressure difference between the aircraft cargo compartment and the air outside during flight may have a significant impact on the pressure dynamics of the compartment. Many cargo compartments are also fitted with pressure equalization valves and emergency relief venting to maintain a constant pressure within the cargo compartment. This preserves the structural integrity of the aircraft in the event of a rapid cargo compartment pressurization or decompression. Further, relief vent activation during discharge could adversely affect agent hold time. The decompression panels of the A-330-200 activate at a pressure difference with respect to the outside air of 10 hPa for blow-in and 80 hPa for blow-out. The conditions of the outside air are those of a typical flight altitude, taken to be 10,000 ft (~3000 m).

The intent in developing this model is to predict the overall pressure dynamics within the cargo compartment during the discharge of FK-5-1-12, a halocarbon clean extinguishing agent. The discharge of halocarbon clean extinguishing agents is characterized by an initial rapid pressure drop followed by a rapid pressure rise within the enclosure [8]. This model will determine if the negative or positive pressures expected during discharge are sufficient to activate the emergency relief venting, as well as the time which the desired agent concentration can be maintained.

Figure 1 - A-330 Forward Cargo Compartment

The cargo compartment considered in this model is the forward cargo compartment of an Airbus A-330-200, which has a volume of approximately 86 m^3. The cargo compartment, shown in Figure 1, is equipped with emergency venting panels, seen on both side walls, and a pressure equalization valve, barely visible on the far wall. The challenges involved with conducting in flight testing makes validating the model difficult. Therefore, the DLR test chamber specified in the US Federal Aviation Administration (FAA) Minimum Performance Standard (MPS) for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems is also modeled [7]. The Trauen Germany located DLR test chamber, shown in Figure 2, has an approximate volume of 57 m^3 and is equipped with a pressure equalization valve, but no emergency venting panels. The leakage from the real aircraft cargo compartment is approximated in the MPS test chamber using perforated ductwork in the shape of a cargo compartment door seal. Air is drawn out of the test chamber through this ductwork at a rate of 1.4 m^3/min [7]. In flight testing will be necessary to determine the real effects of the door seal and the pressure equalization valve.

Background and Theoretical Considerations

This model is a one-zone numerical model solved through conservation of mass and energy during the discharge of FK-5-1-12 into an A-330-200 forward cargo compartment or the DLR test chamber. The conserved quantities are shown in Figure 3 below. The compartment gasses, denoted by the subscript G, are nitrogen and oxygen only prior to discharge with conditions equivalent to those of atmospheric air, denoted by the subscript A, at an elevation of 8,000 ft (~2400 m). Such conditions are what Airbus aircraft are typically designed to, and are maintained through a pressure equalization valve connecting the cargo compartment with the pressurized passenger cabin. The airflow through the pressure equalization valve is denoted by the subscript V for air either entering or exiting the cargo compartment, depending on the pressure difference across the pressure equalization valve. Prior to agent discharge, the airflow entering the compartment through the pressure equalization valve is equivalent to the air leaking from the cargo compartment to the outside of the aircraft through the cargo compartment door seal, denoted by the subscript L. During discharge, agent and nitrogen and oxygen are introduced at known mass flow rates. The heat absorbed by the entering gasses is denoted by the subscript N. The boundary effects of the compartment lining are given as an effective heat transfer rate, denoted by the subscript W.

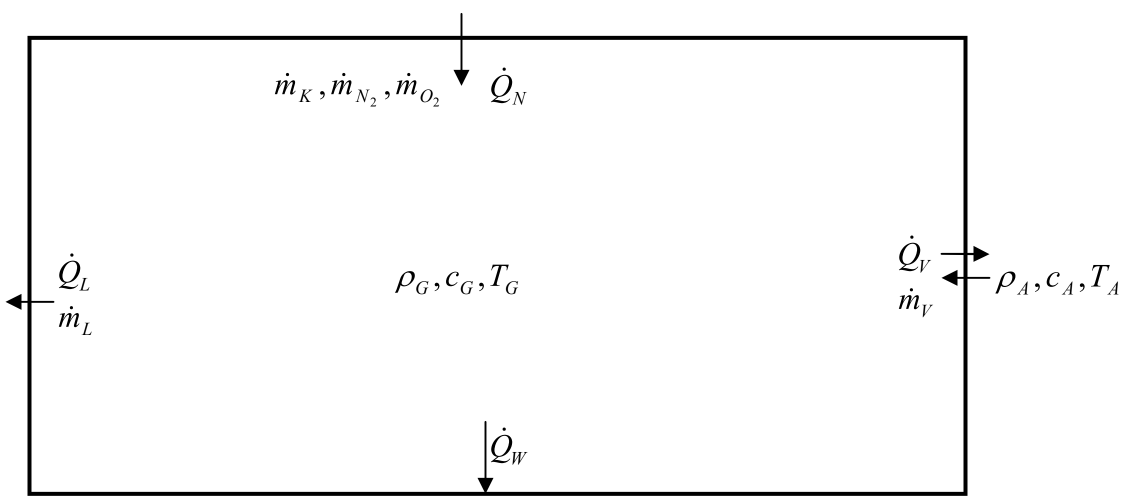

Figure 3 - Compartment Mass and Energy Conservation Diagram

The one zone assumption has been used in several water mist and inert gas discharge and extinguishment models [3, 10]. It is appropriate because the force of the agent being discharged into an enclosure is sufficient to result in near complete mixing of the initial air and incoming agent. All momentum from the agent discharge is assumed to contribute to the continuous mixing within the compartment, allowing the model to be solved without applying a conservation of momentum equation.

The pressure equalization valve does not allow simultaneous flow in and out of the cargo compartment. If the pressure inside the cargo compartment is less than the passenger cabin pressure, air will only flow into the compartment. If the pressure inside the compartment is greater than the passenger cabin pressure, air will only flow out of the compartment. The volumetric flow rate through the pressure equalization valve depends on the magnitude of the pressure difference between the passenger cabin and the cargo compartment. The following data was provided by Airbus for the flow rate through the pressure equalization valve, which is dependant on the pressure difference across the valve and the area of the valve opening. When the pressure difference across the valve is less than 200 Pa, the flow rate through the pressure equalization valve is no greater than 1 m^3/min. The valve begins to open when the pressure difference reaches 200 Pa and continues to open linearly until a pressure difference of 500 Pa. At 500 Pa, the maximum valve opening area is approximately 80 cm^2.

The leakage flow rate is also dependent on the pressure difference between the cargo compartment and the air outside as well as the effective area of the leakages determined from room integrity fan tests. The primary source of leakage from the cargo compartment to the outside is assumed to be the seal of the cargo compartment door, for which the effective leakage area has not been determined. The leakage volumetric flow rate out of the cargo compartment is therefore assumed to be equal to the leakage rate specified in the MPS procedure as 1.4 m^3/min [7]. This assumption does not allow accounting for the variation of flow rate with respect to the pressure difference between the cargo compartment and outside. The assumed leakage rate is significantly greater than those expected for typical aircraft cargo compartments and could affect the peak positive and negative pressures predicted by the model.

Two different primary suppression systems are considered, a twin fluid nozzle introducing both agent and nitrogen, and a single fluid nozzle, introducing primarily agent with a small amount of nitrogen as propellant (.03 kg nitrogen per kg FK-5-1-12). For both primary systems, a secondary suppression system introduces Nitrogen Enriched Air (NEA) (7 vol% residual oxygen) at a flow rate of 1.5 m^3/min until the end of the flight. The twin fluid nozzle introduces agent and nitrogen into the cargo compartment at flow rates of 6 kg/min and 2 kg/min through each nozzle, respectively. The single fluid nozzle introduces agent at a flow rate of 60 kg/min. In both systems, the incoming agent is assumed to be 100% liquid as it enters the cargo compartment. Upon entering the compartment, the agent is assumed to vaporize completely and instantly. This assumption is based on observations of discharge testing with FK-5-1-12 which show the agent vaporizing as it exits the nozzle very rapidly (on the order of 1s) at temperatures well below the boiling point of the agent [9]. All gasses being introduced are assumed to be brought to the compartment gas temperature instantly, allowing the gas mixture within the compartment to be considered a homogenous ideal gas mixture.

In the hold time models provided by NFPA and ISO, the loss of agent out of the enclosure is hydrostatically driven [2, 5, 6]. For heavier than air halocarbons, the dense agent/air mixture exerts a positive pressure relative to the exterior on the enclosure boundaries, pushing it out through leakages in the lower enclosure boundaries. This creates a negative pressure in the upper portions of the enclosure relative to the exterior and clean air is drawn in through leakages in the upper enclosure boundaries. In an aircraft cargo compartment, the pressure difference between the inside and outside is far greater than the pressure difference resulting from the change in density of the air in an enclosure at ground level. Therefore, it is assumed that gravity will not have a significant impact on the distribution of agent during discharge or the leakage out of the compartment after the end of discharge. The same equations used to predict the pressure and agent concentration during discharge are extended through time to determine the hold time.

Mathematical Model

The model is developed from conservation of mass and energy in the compartments described above. At any given time the total mass of gasses in the compartment is the sum of the mass of oxygen, nitrogen, and agent, denoted by the subscripts O_2, N_2, and K, respectively. Trace gasses have been neglected. Over a very short time period during discharge, the rate of change of the total mass, m_{tot}, of gasses in the compartment can be expressed in terms of the change in density of each gas species, ρ_i, in the constant volume, V, of the compartment as;

$$\frac{dm_{tot}}{dt} = V\left(\frac{d\rho_{O_2}}{dt} + \frac{d\rho_{N_2}}{dt} + \frac{d\rho_K}{dt}\right) \quad \textbf{(1)}$$

The species density rate of change for oxygen can be expressed;

$$\frac{d\rho_{O_2}}{dt} = \frac{\left(\dot{V}_{O_2,NEA}\cdot\rho_{O_2,A} + \dot{V}_V\cdot\rho_{O_2,V} - \dot{V}_L\cdot\rho_{O_2}\right)}{V} \quad \textbf{(2)}$$

The first term represents the oxygen being introduced by the NEA system, the second term represents the oxygen entering or exiting the compartment through the pressure equalization valve and the last term represents the oxygen leaking out of the compartment. For nitrogen, the density rate of change is similar but includes a term, $\dot{m}_{N_2}$, representing the nitrogen being added through the nozzle;

$$\frac{d\rho_{N_2}}{dt} = \frac{\left(\dot{m}_{N_2} + \dot{V}_{NEA}\cdot\rho_{N_2,A} + \dot{V}_V\cdot\rho_{N_2,V} - \dot{V}_L\cdot\rho_{N_2}\right)}{V} \quad \textbf{(3)}$$

The density of agent in the compartment is only changed by the agent being introduced at the nozzle, $\dot{m}_K$, the agent exiting through the pressure relief valve, and the agent leaking out of the cargo compartment;

$$\frac{d\rho_K}{dt} = \frac{\left(\dot{m}_K + \dot{V}_V \cdot \rho_{K,V} - \dot{V}_L \cdot \rho_K\right)}{V} \tag{4}$$

The internal energy of the compartment, U, at any given time is expressed in terms of the gas temperature with respect to a reference temperature, T_{ref}, assumed to be 0 K, and the specific heat of the gas mixture as;

$$U = m_{tot} \cdot c_G \left(T_G - T_{ref}\right) \tag{5}$$

The specific heat of the gas mixture, c_G, is calculated as the sum of the mole traction weighted specific heats of each species where w_i is the molecular weight of gas species *i*;

$$c_G = \frac{\rho_{O_2} \cdot w_{O_2} \cdot c_{O_2} + \rho_{N_2} \cdot w_{N_2} \cdot c_{N_2} + \rho_K \cdot w_K \cdot c_K}{(\rho_{O_2} \cdot w_{O_2} + \rho_{N_2} \cdot w_{N_2} + \rho_K \cdot w_K)} \tag{6}$$

The specific heats are assumed to be constant for all three gas species, at values of 0.93 J/gK for oxygen, 1.04 J/gK for nitrogen, and 0.88 J/gK for FK-5-1-12, for both the compartment and ambient gasses. The energy balance of the compartment is expressed by the following conservation of energy equation;

$$\frac{dU}{dt} = \dot{Q}_V - \dot{Q}_L - \dot{Q}_N - \dot{Q}_W \tag{7}$$

The energy transfer rates from the air being added to pressurize the compartment and from the air entering and exiting through the pressure equalization valve are expressed as;

$$\dot{Q}_V = \dot{V}_V \cdot \rho_V \cdot c_V \cdot T_V \tag{8}$$

$$\dot{Q}_L = \dot{V}_L \cdot \rho_G \cdot c_G \cdot T_G \tag{9}$$

When the pressure difference across the pressure equalization valve is positive, the flow is entering the cargo compartment. Therefore, the density, specific heat, and temperature values are those of ambient air. When the pressure difference is negative, air is leaving the cargo compartment, and values are used for the gas mixture inside the compartment. The volumetric flow rate, as described in the discussion above, has three distinct regimes depending on the magnitude of the pressure difference and is expressed as;

$$\dot{V}_V = \begin{cases} \dot{V}_O & |\Delta P_V| \le 200 \\ \left(\frac{|\Delta P_V| - 200}{500 - 200}\right) \cdot A_V \cdot C_V \cdot \left(\frac{2 \cdot |\Delta P_V|}{\rho_V}\right)^{0.5} + \dot{V}_O & 200 \le |\Delta P_V| \le 500 \\ A_V \cdot C_V \cdot \left(\frac{2 \cdot |\Delta P_V|}{\rho_V}\right)^{0.5} + \dot{V}_O & |\Delta P_V| \ge 500 \end{cases} \quad \textbf{(10)}$$

The overall heat loss rate through the walls of the compartments is expressed as;

$$\dot{Q}_W = h_{eff} \cdot A_{tot}(T_G - T_W) \quad \textbf{(11)}$$

Where h_{eff} is an effective heat transfer coefficient, A_{tot} is the compartment surface area, and T_W is the wall temperature. The rate of heat absorption during discharge from the nozzle is expressed in terms of the energy required to vaporize the liquid agent, with a heat of vaporization, L_V, and the energy required to bring the gasses entering through the nozzles to the compartment gas temperature as;

$$\dot{Q}_N = \dot{m}_K \cdot L_V + \dot{m}_K \cdot c_K(T_G - T_A) + (\dot{m}_{N_2} + \dot{m}_{N_2,NEA}) \cdot c_{N_2}(T_G - T_A) + \dot{m}_{O_2,NEA} \cdot c_{O_2}(T_G - T_A) \quad \textbf{(12)}$$

Rearranging equations 5 and 7 allows the transient temperature variation to be expressed as;

$$\frac{dT_G}{dt} = \frac{dU}{dt} \cdot \frac{1}{m_{tot} \cdot c_G} \quad \textbf{(13)}$$

The compartment pressure is equal to the sum of the partial pressures, p_i, for each gas species *i*, which are expressed in terms of the density, molecular weight, ideal gas constant, R, and gas temperature as;

$$P = \sum p_i \quad \textbf{(14)}$$

$$p_i = \frac{\rho_i \cdot R \cdot T_G}{w_i} \quad \textbf{(15)}$$

Substituting equation 15 into equation 14 and applying the product rule to derive equation 14 with respect to time yields the following expression for the transient pressure of the gas mixture in the cargo compartment;

$$\frac{dP}{dt} = \sum_i \left(\frac{\frac{d\rho_i}{dt}}{w_i}\right) \cdot R \cdot T_G + \sum_i \left(\frac{\rho_i}{w_i}\right) \cdot R \cdot \frac{dT_G}{dt} \quad \textbf{(16)}$$

Model Inputs and Predictions

Both the DLR MPS test chamber and the A-330-200 cargo compartment are modeled with both primary suppression systems. In all four scenarios, the door seal leakage rate is specified as 1.4 m^3/min. In reality, the DLR chamber is much less airtight than the cargo compartment, however in this model, they are assumed to have equivalent leakages. The temperature of the compartment walls and the temperature of the gasses entering at the nozzle are all assumed to be equal to the ambient air temperature. Each scenario was modeled for 0%, 30%, 60%, and 90% cargo loading volume. The four scenarios and their input parameters are summarized in Table 1 below.

Table 1 - Predicted Scenarios

	Enclosure	Initial P [bar]	Primary System	Nozzles	Discharge Time [s]	Nitrogen Flow Rate [kg/min]	FK-5-1-12 Flow Rate [kg/min]
Scenario 1	DLR	1.01	Twin Fluid	4	120	8	24
Scenario 2	DLR	1.01	Single Fluid	2	30	1.8	60
Scenario 3	A-330-200	0.74	Twin Fluid	6	120	12	36
Scenario 4	A-330-200	0.74	Single Fluid	3	30	1.8	60

This model predicts that for the empty DLR test chamber, discharge of either primary suppression system would result in blow-in activation of the decompression panels. In the empty A-330-200 cargo compartment, only the single fluid system would cause blow-in activation of the decompression panels. This is likely due to the fact that the DLR chamber initial pressure is equal to the outside air pressure, while the A-330-200 is pressurized above the conditions of the outside air. For all scenarios with no cargo loading, blow-out was not predicted. The pressure dynamics for the four empty scenarios are illustrated in Figure 4.

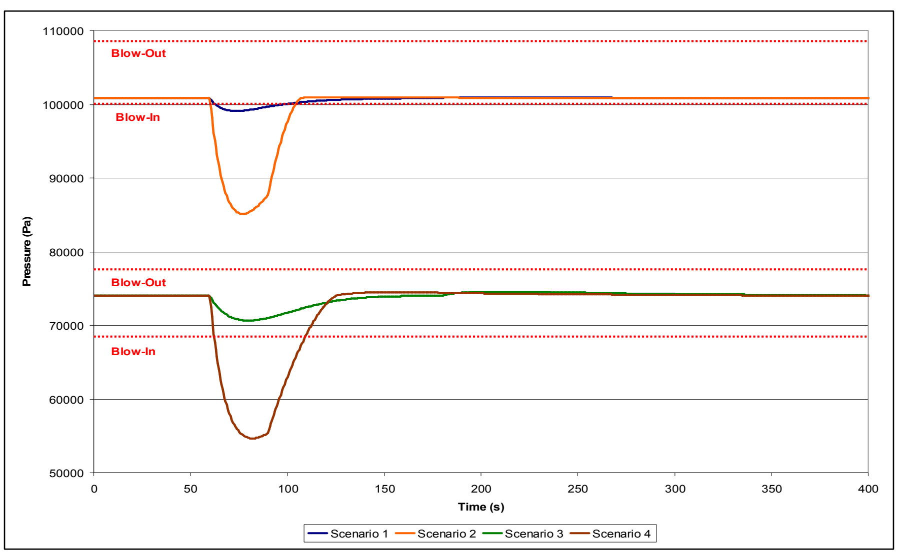

Figure 4 - Scenario Pressure Dynamics

The amount of cargo loading is predicted to have a more significant impact on the timing of the pressure drop and rise than on the actual values of the pressure drop or rise. As the cargo loading is increased, the time it takes for the pressure to reach its low and high values decreases. Increased loading also increases the peak positive pressure experienced in the cargo compartment while there is almost no change in the maximum negative pressure load. The pressure dynamics of the A-330-200 with the twin fluid suppression system at different cargo loading volumes are illustrated in Figure 5.

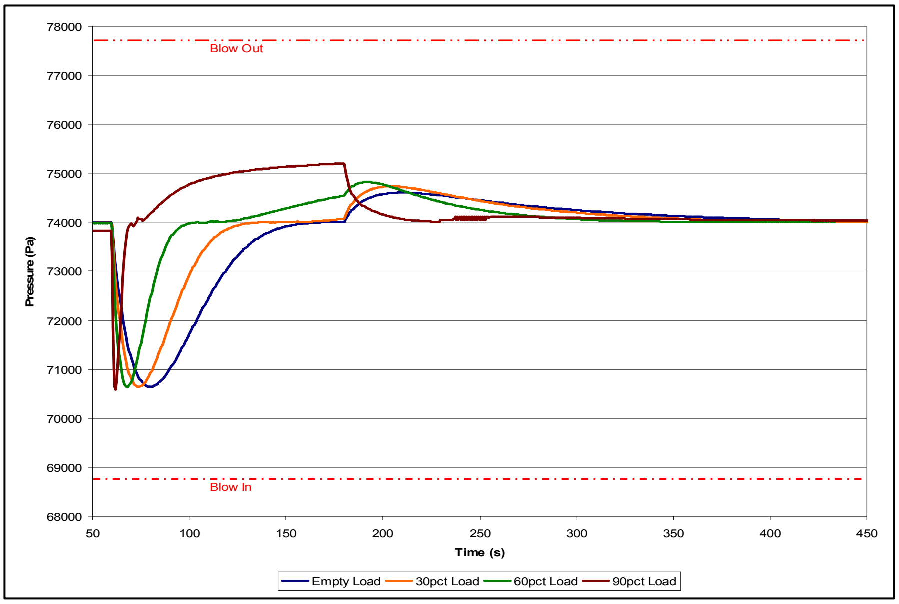

Figure 5 - Scenario 3 Pressure Dynamics of Different Cargo Load Volumes

Conclusion

The model presented for halocarbon clean extinguishing agent discharged into an aircraft cargo compartment in flight has been used to simulate two different primary suppression systems in both the ground level DLR MPS test chamber and an A-330-200 cargo compartment in flight. The model predicts that the cargo compartment in flight equipped with a twin fluid suppression system will not activate the emergency pressure relief venting at any point during discharge irrespective of the cargo load volume.

Many assumptions, however, have been made about the input parameters for the model which are not based on empirical data. The mass flow rates of agent and nitrogen from nozzle design specifications are assumed, having yet to be confirmed by testing. The cargo compartment door seal leakage flow rate is assumed to be equal to that specified in the FAA MPS for grounded test chambers. In reality, the flow rate out of the door seal is dependent upon the pressure difference between the cargo compartment and the outside. To more accurately model this flow rate, the equivalent leakage area of the door seal should be determined by performing fan tests on the cargo compartment [2, 6]. These tests should also be performed on the DLR test chamber. The pressure equalization valve is characterized using several assumptions based on incomplete qualitative information. The variation of flow rate through the valve with respect to the pressure difference across the valve should also be tested to improve the accuracy of the model.

In addition to evaluating the input parameter accuracy, it is desirable to validate the entire model via full scale discharge tests. This can be done using the model predictions for the MPS test chamber, however the test chamber is much less airtight than the A-330-200 cargo compartment, and the results of testing in this chamber may not necessarily validate the entire model. Ideally, full scale testing conducted in a real cargo compartment in flight would be best for validating the model.

In the future, the discharge model presented here could be extended to include extinguishment by including the presence of fire in the cargo compartment and the heat and products of combustion released into the compartment [3, 10]. This can be done by including terms in the conservation equations for the oxygen consumed and the heat and products of combustion released by the fire, which have a significant effect on the pressure and temperature dynamics of the compartment.

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Nomenclature

Symbols

A	Area [m^2]
c	Specific heat [kJ/kgK]
C	Flow Coefficient [0.61]
h_{eff}	Compartment wall effective heat transfer coefficient [0.08 kW/m^2K]
L_V	FK-5-1-12 heat of vaporization [88.0 kJ/kg]
m_{tot}	Total compartment gas mixture mass [kg]
$\dot{m}$	Mass flow rate [kg/min]
P	Pressure [Pa]
ΔP	Pressure Difference [Pa]
p	Partial pressure [Pa]
$\dot{Q}$	Heat transfer rate [kW]
R	Ideal gas constant [8.314 m^3Pa/molK]
ρ	Density [kg/m^3]
T	Temperature [K]
U	Internal energy [kJ]
V	Volume [m^3]

$\dot{V}$	Volume flow rate [m^3/min]
w	Molecular weight [kg/kmol]

Subscripts

A	Ambient Air
G	Gas Mixture
i	Gas Species
K	FK-5-1-12
L	Door Seal Leakage
N	Nozzle
NEA	Nitrogen Enriched Air
N_2	Nitrogen
O	Initial or Baseline
O_2	Oxygen
ref	Reference
tot	Total Compartment
V	Pressure Equalizing Valve
W	Wall

References

1. Hetrick, T. "Investigation of Hold Time Calculation Methodologies for Total Flooding Clean Extinguishing Agents", SUPDET Proceedings 2007. 2007.

2. "ISO 14520-1: Gaseous Fire Extinguishing Systems - Physical Properties and System Design - Part 1: General Requirements, Annex E." International Standards Organization. 2006.

3. Li, Y.F., Chow, W.K. "A Zone Model in Simulating Water Mist Suppression on Obstructed Fire." Heat Transfer Engineering. Vol. 27, No. 10. 2006. 99-115.

4. Moran, M.J. and Shapiro, H.N. "Fundamentals of Engineering Thermodynamics." 6th Edition. John Wiley & Sons, Inc. 2008.

5. Mowrer, F.W. "Analysis of Vapor Density Effects on Hold Times for Total Flooding Clean Extinguishing Agents." Halon Options Technical Working Conference, 16th Proceedings. May 16-18, 2006, Albuquerque, NM, USA. 2006. 1-12.

6. "NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems, Annex C." National Fire Protection Association. 2008.

7. Reinhardt, J.W. "Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems." 2nd Update. US Department of Transportation Federal Aviation Administration. June 2005.

8. Robin, M.L., et. al. "Pressure Dynamics of Clean Agent Discharges." Halon Options Technical Working Conference, 15th Proceedings. May 24-26, 2005, Albuquerque, NM, USA. 2005. 1-11.

9. Schmeer, J.S., et. al. "Consideration of Liquid to Gas Phenomena for a Sustainable, High-Boiling, Tropodegradeable Halocarbon." Halon Options Technical Working Conference, 16th Proceedings. May 16-18, 2006, Albuquerque, NM, USA. 2006.

10. Vaari, J. "A transient one-zone computer model for total flooding water mist fire suppression in ventilated enclosures." Fire Safety Journal. Vol. 37, 2002. 229-257.

11. Yoon, S.S., et. al. "A Modeling Investigation of Suppressant Distribution from a Prototype Solid-Propellant Gas-Generator Suppression System into a Simulated Aircraft Cargo Bay." Drying Technology. Vol. 25, 2007. 1011-1023.