Springer

Journal of Mechanical Science and Technology

Journal of Mechanical Science and Technology 23 (2009) 1877~1884

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-009-0618-7

Numerical analysis of flow characteristics of fire extinguishing agents in aircraft fire extinguishing systems †

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(Manuscript Received March 30, 2009; Revised May 6, 2009; Accepted May 6, 2009)

Abstract

If fire breaks out on an airplane, a large amount of fire extinguishing agents should be discharged within a very short time. For effective fire extinguishing, increased discharge velocity of the fire extinguishing agents is required. This can be achieved by using a large-sized vessel in which the fire extinguishing agents are highly pressurized by non-combustible gases. It is important to understand the flow characteristics of a fire extinguishing system for optimal system design. This study reports a numerical analysis of the flow characteristics of an airplane fire extinguishing system using halon-1301 as a fire extinguishing agent. The unsteady flow model was simulated with the general-purpose software package "FLUENT", to study the flow characteristics of the fire extinguishing agents in the system. The effects of the rupture surface area and tube diameter on the flow characteristics were investigated for optimal system design. From the analysis results, it was clarified that the characteristics of the halon discharge from the end of tube are very sensitive to the rupture surface area and significantly affected by the tube diameter.

Keywords: Aircraft fire extinguishing system; Fire extinguishing agent; Halon-1301; Flow characteristics; Numerical analysis

1. Introduction

Airplane fire extinguishing systems demand high reliability and accuracy of operation. Fires that occur in flight accidents necessitate thorough research into fire extinguishing systems. All possible design methods must be used to control and prevent the occurrence of fires in airplanes. An important element in the design of fire extinguishing systems is the method used to reduce the effects of a fire. A fire extinguishing system is designed to meet standards that serve to eliminate, or at least diminish, ignition-energy sources [1-4].

Hariram [3] investigated various fire protection methods, including eliminating fuels and ignition sources to reduce flammability, temperature control, fire detection and fire extinguishing systems in airplanes. Friedman [4] reviewed fire safety in the spacecraft environment, including fire prevention, the influence of low gravity on fire behavior, fire detection in space and fire control and suppression using fire-extinguishing agents. This review scrutinizes the use of halon-1301 ($CBrF_3$) as a fire extinguishing agent. Halon-1301 is an extremely efficient fire extinguisher and chemical inhibitor of combustion reactions. Santrock and Hodges [5] evaluated the performance of an automatic fire protection system installed in the engine compartment of large vehicles in a full-scale vehicle crash test and a static vehicle fire test. According to their results, the systems were more successful in large vehicles than in light trucks, due to the fact that most fires in large vehicles did not involve a crash and significant deformation.

Of the many types of fire extinguishing chemicals, halons are the most widely used fire extinguishing

† This paper was presented at the 7th JSME-KSME Thermal and Fluids Engineering Conference, Sapporo, Japan, October 2008.

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agent in fire extinguishing systems for aircraft and automobile engines since they do not leave any residue, can totally flood cluttered compartments, exhibit high performance and are presumed to have low toxicity.

Bennett [6] studied the implications of recent analyses of toxicity and environmental impacts of in-car fire extinguishing systems used in motorsports competition, and investigated issues related to the health and occupational exposure of drivers to halon-1211, halon-1301, HFC-236fa (trade name FE-36), gelled suspension of HFC-236fa and other fire-extinguishing agents. Friedman and Dietrich [7] investigated ignition and flame spread of fuels in a microgravity environment, using small-scale tests in drop towers. They showed that, for a halon-1301 dilution, the quantity needed for suppression was appreciably smaller in microgravity than in normal gravity.

In airplane fire extinguishing systems, 90% of extinguishing agents should be discharged within a very short time, for optimal fire extinguishment. In general, for effective fire extinguishment, the discharging velocity of fire extinguishing agents must be increased, by using large-sized vessels in which the fire extinguishing agents are highly pressurized by non-combustible gases. In addition, large amounts of extinguishing agents are required, and tubes with large diameters must be used to reduce flow resistance. However, optimally designed airplane fire extinguishing systems should have minimal weight, which increases the distance that the airplane can travel. In designing a fire extinguishing system, it is important to balance the reduction of weight against the flow necessary for effective fire extinguishing. In the literature, few studies have focused on performance analysis and optimal design of fire extinguishing systems. Consequently, there is currently insufficient quantitative data on the flow characteristics of airplane fire extinguishing systems.

In this study, a numerical analysis of flow characteristics was carried out to facilitate the design of airplane fire extinguishing systems, using halon-1301 as a fire extinguishing agent. In particular, the effects of the rupture surface area and tube diameter on the flow characteristics were investigated numerically.

2. Model of fire extinguishing system

Fig. 1 shows the configuration of the airplane fire extinguishing system used in this study. The system is composed of a vessel to hold fire extinguishing agents, a tube connected to the vessel to transfer fire extinguishing agents to the fire extinguishing target, such as an engine room, and the rupture surface, installed between the lower part of the vessel and the tube inlet. When the fire extinguishing system starts to operate, the rupture surface opens as its surface is ripped off by external forces, and the fire extinguishing agents leave the vessel through the opened area of the rupture surface, move along the tube, discharge from the tube end, and finally jet to the fire extinguishing target.

Fig. 2 shows the vessel-tube configuration and the schematics of the rupture part. The rupture part is a hexagon, and when the fire extinguishing system is operated, its surface rips into 6 triangular pieces. Once the rupture surface opens, the fire extinguishing agents in the vessel are transferred through the tube to

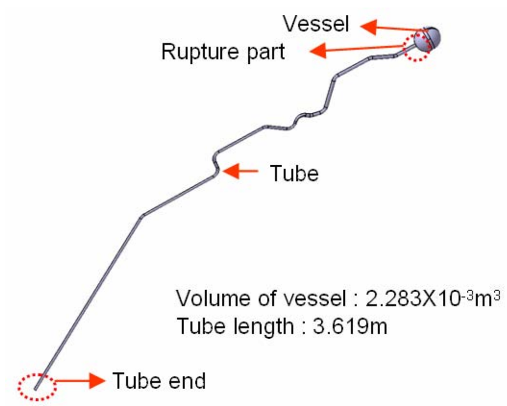


Fig. 1. Configuration of airplane fire extinguishing system.

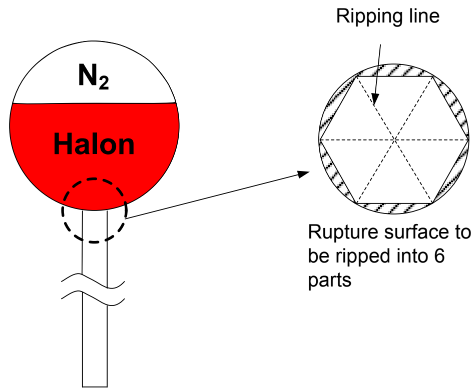


Fig. 2. Outlines of vessel-tube connection and details of rupture surface.

Table 1. Analysis conditions and initial values.

Parameters	Conditions
Rupture surface area ($\times 10^{-6}$ m^2)	3/6 (219), 4/6 (292), 5/6 (365), 6/6 (438) (fully opened)
Tube diameter (inch)	1 and 1.2
Tube length (m)	3.619
Vessel volume ($\times 10^{-3}$ m^3)	2.283
N_2 gas pressure (MPa)	4.1
Tube end pressure	Atmospheric pressure

the fire extinguishing target. The broken line on the rupture surface (right-hand side in Fig. 2) indicates grooves that are inscribed so that they rip easily. The rupture part is designed so that its surface should be fully opened when the fire extinguishing system starts. However, in rare cases, the rupture surface only opens partially due to incomplete ripping. In this study, simulations were performed to investigate the effects of the opening area on the discharge flow characteristics. The fully opened rupture surface will be denoted by 6/6, and the partially opened cases will be denoted by 3/6, 4/6 and 5/6, as listed in Table 1.

The fire extinguishing agents discharging from the vessel are transferred to the fire extinguishing target through the tube. Therefore, the volume of the tube affects the time elapsed before the fire extinguishing agent is discharged from the end of the tube. The total volume of the fire extinguishing agent (V_{total}) in the system, as shown in Fig. 1, is composed of:

$$V_{total} = V_{vessel} + V_{tube} + V_{dischged} \tag{1}$$

where V_{vessel} is the volume of the fire extinguishing agent in the vessel, V_{tube} is the volume in the tube, and $V_{dischged}$ is the discharging volume. The volume of the fire extinguishing agent that discharges from the end of the tube is significantly affected by the tube volume, which is proportional to the square of its diameter. For this reason, two tube diameters, 1 inch and 1.2 inch, were used to investigate the effect of the tube volume on the discharge characteristics of the fire extinguishing agent. The volume of the vessel was 2.283×10^{-3} m^3. The vessel was 68% filled with halon-1301 (hereafter halon) as a fire extinguishing agent; the remaining space was filled with nitrogen gas. The initial pressure of the nitrogen gas in the vessel was 4.1 MPa, providing the driving force to expel the halon. The tube length was 3.619 m, and the tube volumes were 1.585×10^{-3} and 2.640×10^{-3} m^3 for the 1 and 1.2 inch tube diameters, respectively. The analysis conditions and initial values are summarized in Table 1.

3. Numerical analysis

3.1 Governing equations and boundary conditions

In this study, a 3-dimensional unsteady model was simulated, using the general-purpose software package FLUENT to investigate the flow characteristics of the halon in the fire extinguishing system. When the fire extinguishing system starts to operate and the rupture surface is opened, the halon, pressurized by nitrogen gas, leaves the vessel through the opened area of the rupture surface and moves along the tube. As time elapses, the nitrogen gas also enters the tube, and two-phase flow occurs in the tube. The Volume of Fluid (VOF) method [8] was used to analyze the two-phase flow of the liquid and gas.

The employed mathematical model was based on the 3-D solution of coupled partial differential equations, which describe the conservation of mass and momentum, and the VOF around the rupture part and in the tube. The continuity equation is written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{2}$$

The momentum equation is written as

$$\frac{\partial}{\partial t}(\rho u_j) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i}\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \rho g_j + F_j \tag{3}$$

3.2 Interface tracking using VOF method

The VOF approach is that a two-phases system can be represented as a mixture of phases in which the phases-fraction distribution includes sharp transitions between the phases. Therefore, the interfaces between the phases are tracked by the solution of a continuity equation for the volume fraction of one of the phases. For the qth phase, this volume fraction equation has the following form:

$$\frac{\partial \alpha_q}{\partial t} + u_i \frac{\partial \alpha_q}{\partial x_i} = S\alpha_q \tag{4}$$

The qth fluid's volume fraction in the cell is denoted as α_q, which can be described by one of the three following conditions:

α_q = 0 the cell is empty (of the qth fluid)

α_q = 1 the cell is full (of the qth fluid)

$0 < \alpha_q < 1$ the cell contains the interface between the fluids.

Based on the local value of α_q, the appropriate properties and variables are assigned to each control volume within the domain.

Even though the VOF interface tracking method is a flexible approach for simulation of two-phases systems with free surfaces, in particular for circumstances that the surface tension effects are not dominant, the challenges of the VOF methodology relates to the accuracy of the numerical scheme, in order to ensure that the interface remains sharp and mesh alignment bias.

3.3 Numerical process

For the simulation of the two-phase flow of a halon and a nitrogen gas, the VOF method was applied, with unsteady conditions. A grid was constructed throughout the structure, and was made more dense near the rupture part, where the flow starts and changes dramatically within a small volume. The simulation was carried out using a computer with a 3.0 GHz P4 CPU, and took about 100 hours to solve one case due to very dense grids and small time step size.

4. Results and discussion

4.1 Flow characteristic in vessel and tube

Fig. 3 shows the progress of the boundary surface between the nitrogen gas (upper part) and the halon (lower part) in the vessel after the rupture surface was ripped fully open (6/6), with a 1 inch tube diameter. As time elapses, the boundary surface moves downward toward the rupture part, the exit of the vessel, changes into a downward convex surface around 0.05 seconds after the fire extinguishing system is engaged (hereafter all times are quoted as the elapsed time since the fire extinguishing system was engaged) and finally reaches the rupture surface after 0.15 seconds. At this time, a large amount of the halon still remains in the vessel. After 0.15 seconds, both the halon and the nitrogen gas simultaneously enter the tube, and two-phase flow behavior begins in the tube. The amount of halon remaining in the vessel after the nitrogen gas enters the tube is related to the internal geometry of the vessel, which strongly affects the discharging characteristics of the fire extinguishing agents.

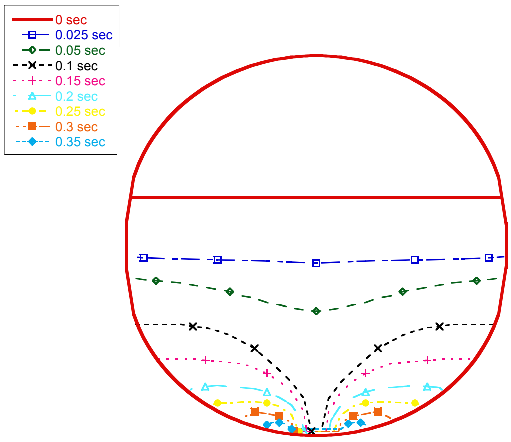


Fig. 3. Movement of the boundary surface in the vessel, for a rupture surface of 6/6 and 1 inch tube diameter.

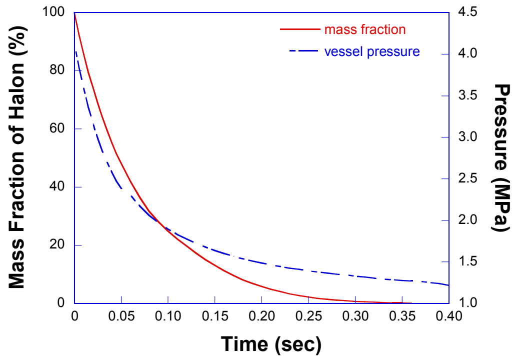


Fig. 4. Variation of halon mass fraction in the vessel, for a rupture surface of 6/6 and 1 inch tube diameter.

Fig. 4 shows the mass fraction of the halon and the pressure of the nitrogen gas in the vessel against elapsed time, for a 6/6 rupture surface and a 1 inch tube diameter. The mass fraction of the halon is defined as the ratio of the mass of the halon in the vessel to the total mass of the halon. The nitrogen gas pressure in the vessel steeply decreases with elapsed time immediately after the rupture surface opens, and then decreases gradually. The remaining amount of halon in the vessel, which is inversely proportional to the amount discharged through the rupture surface, falls rapidly to 25% of its initial value during the first 0.1 seconds. After 0.15 seconds, it decreases slightly when the nitrogen gas enters the tube, due to decreased nitrogen gas pressure. After 0.4 seconds, most of the halon has exited from the vessel, and only

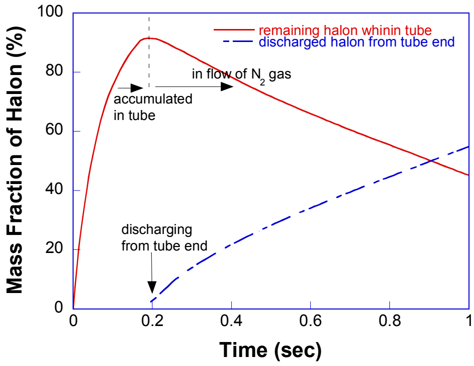


Fig. 5. Time evolution of the halon mass fraction in the tube and discharging from the tube end, for a rupture surface of 6/6 and 1 inch tube diameter.

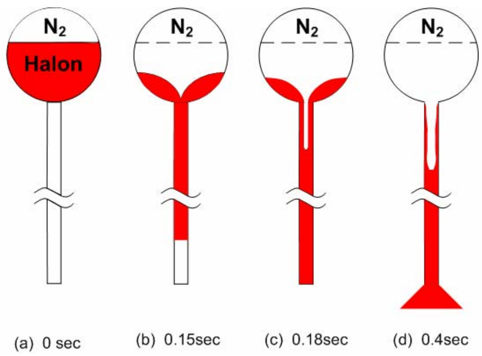


Fig. 6. Flow behavior in the vessel and tube, for a rupture surface of 6/6 and 1 inch tube diameter.

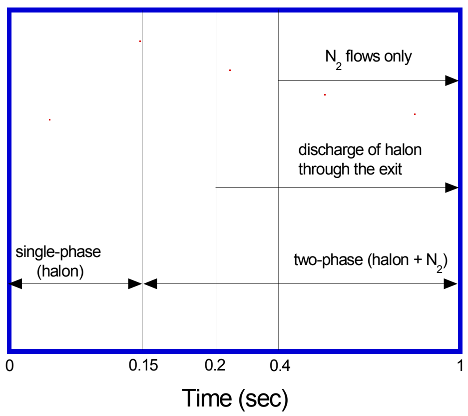


Fig. 7. Diagram of flow behavior over time at the rupture surface and the tube end, for a rupture surface of 6/6 and 1 inch tube diameter.

the nitrogen gas remains in the vessel.

Fig. 5 shows the mass fraction of the halon in the tube and the amount of halon discharged from the end of the tube for a 6/6 rupture surface and a 1 inch tube diameter. The mass fraction of the halon in the tube rises rapidly to a maximum value of 91% just before the halon is discharged from the end of tube, and then decreases smoothly, as the halon stops discharging from the vessel and begins discharging from the end of tube. The slow decrease of the mass fraction of halon in the tube leads to a decreased amount of halon discharging from the end of tube. Hence, it is necessary to increase the nitrogen gas pressure or decrease the volume of the tube to facilitate rapid halon discharge from the end of tube within a very short time. Of course, increased flow resistance due to a decreased tube diameter should also be taken into consideration for optimal system design. The halon starts to discharge at the end of tube after 0.18 seconds, and 60% of the halon is discharged during the first second. In this study, a period of 1 second was taken to be the critical time for performance analysis of the fire extinguishing system.

Fig. 6 shows a schematic of the flow behavior of the halon in the vessel and the tube, for a 6/6 rupture surface and a 1 inch tube diameter. The broken line in the vessel indicates the initial boundary surface. The boundary surface changes into a downward convex surface as time elapses, and a large amount of the halon remain in the vessel when the nitrogen gas begins to enter the tube. As the nitrogen gas and the halon simultaneously enter the tube, the flow in the tube exhibits two-phase annular flow. Almost all of the halon has been discharged into the tube after 0.4 seconds have elapsed.

Fig. 7 shows a diagram of the flow behavior of the halon over time, both in the vessel and tube. At 0.15 seconds, the whole volume of the tube is filled with only halon; after 0.15 seconds, the nitrogen gas and halon both enter the tube, resulting in two-phase flow. The halon starts to discharge at the end of tube after 0.2 seconds, and there is only nitrogen gas in the vessel after 0.4 seconds.

4.2 Effects of rupture surface area on the flow characteristics

Fig. 8 shows the mass fraction of the halon in the vessel with as the rupture surface area is varied from 3/6 to 6/6, as described in Table 1. The effect of the rupture surface area on the halon discharge characteristics was investigated with the 1 inch diameter tube. As the rupture surface area decreases, the discharge of

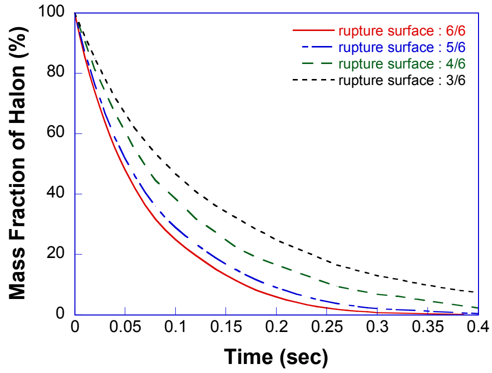
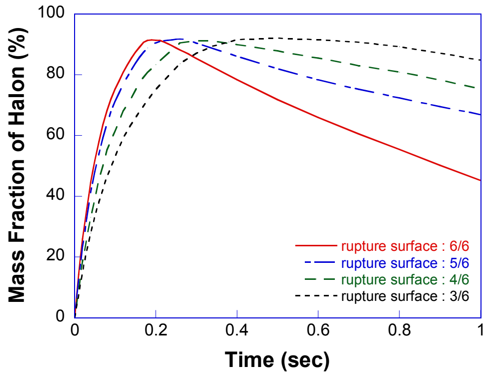
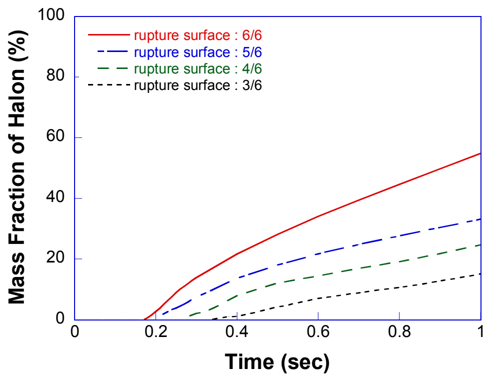


Fig. 8. Halon mass fraction in the vessel over time, for the 1 inch tube diameter and various rupture surface areas (3/6, 4/6, 5/6 and 6/6).



(a) Mass fraction in tube



(b) Mass fraction at tube end

Fig. 9. Halon mass fraction at the tube end, for the 1 inch tube diameter and various rupture surface areas (3/6, 4/6, 5/6 and 6/6).

halon from the vessel takes longer, due to increased flow resistance. The halon is completely discharged from the vessel after 1, 0.7, 0.5 and 0.4 seconds for rupture surface areas of 3/6, 4/6, 5/6 and 6/6, respectively.

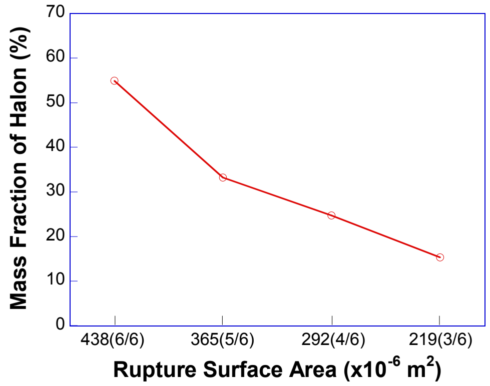


Fig. 10. Mass fraction of halon discharging from tube end at 1 second with rupture surface area (3/6, 4/6, 5/6 and 6/6) for 1 inch tube diameter.

Fig. 9 shows the effect of surface area on the mass fraction of halon in the tube and the amount of halon discharged from the end of tube for the 1 inch diameter tube. The mass fraction of the halon in the tube, as shown in Fig. 9(a), exhibits an immediate steep increase to a maximum value of 91%, just before the halon is discharged from the end of tube. However, as the rupture surface area decreases, the time when the halon mass fraction reaches its maximum is retarded, which indicates that longer times are required to fill the tube with halon. After the peak, the halon mass fraction in the tube decreases more slowly as the rupture surface area decreases, as the amount of halon discharged from the end of tube is decreased. Fig. 9(b) shows the onset of discharge from the end of tube; the onset times of discharge from the end of tube are estimated to be 0.18, 0.2, 0.26 and 0.32 seconds for rupture surface areas of 6/6, 5/6, 4/6 and 3/6, respectively. The rate of discharge after the onset time increases as the rupture surface area increases.

Fig. 10 shows the mass fraction of the halon discharged from the end of tube after 1 second, for the 1 inch diameter tube and various rupture areas. The halon mass fractions discharged after 1 second were 54.9, 33.2, 24.7 and 12.3% of the initial amount of halon, as the rupture surface area decreased from 6/6 to 3/6. There is a 39.6% difference in discharged halon mass fraction between rupture surface areas of 6/6 and 3/6. It is noted that there is a rapid drop between 6/6 and 5/6, which indicates that the halon discharge characteristics are very sensitive to the rupture surface area. Consequently, the performance of the fire extinguishing systems absolutely depends on the reliability of the rupture part, which should be completely

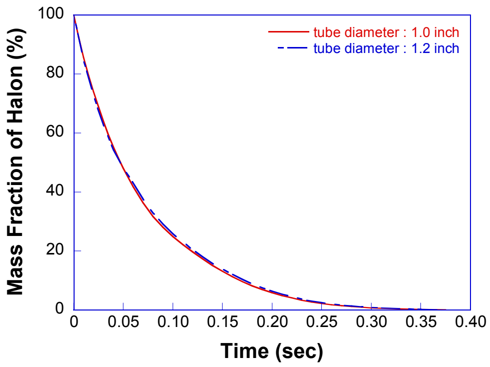


Fig. 11. Variation of mass fraction of halon in vessel for two tube diameters of 1 and 1.2 inch at fixed rupture surface 6/6.

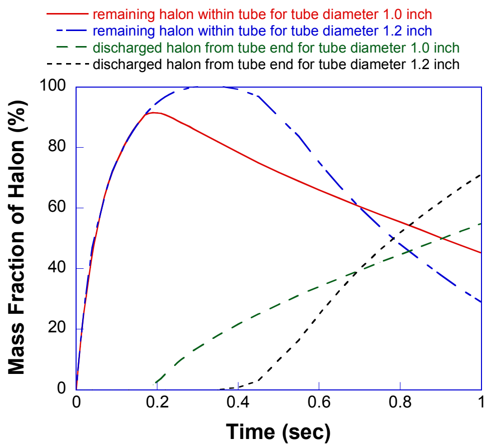


Fig. 12. Time evolution of mass fractions of halon in tube and discharging from tube end for two tube diameters of 1 and 1.2 inch at fixed rupture surface 6/6.

ripped off so that the rupture surface is fully open.

4.3 Effects of tube diameter on halon discharging

Fig. 11 shows the halon mass fraction in the vessel against the elapsed time, for a 6/6 rupture surface and the two tube diameters, 1 inch and 1.2 inches. The halon mass fraction in the vessel shows similar time dependencies for both tube diameters. This similarity is due to the fact that the rupture surface is fixed to 6/6, and flow resistance of the empty tube is a minor effect. The halon from the vessel is completely discharged into the tube at the same time, 0.4 seconds, for the two tube diameters.

Fig. 12 shows the halon mass fraction in the tube and discharged from the end of the tube, for the two tube diameters of 1 and 1.2 inches at a fixed rupture surface of 6/6. The increase in the halon mass fraction at early times is similar for the two tube diameters until 0.18 seconds, when a maximum value of 91% is achieved in the 1 inch diameter tube. The mass fraction continues increasing in the 1.2 inch diameter tube, reaching 100% at 0.4 seconds. For the 1 inch diameter tube, the maximum value of the halon mass fraction is limited to 91%, even though the tube volume is almost the same (1.01 times) as that of the halon. This can be explained by the inflow of nitrogen gas into the tube and the discharge of halon from the tube end. On the other hand, the volume of the 1.2 inch diameter tube is nearly 1.68 times that of the halon, so the maximum value of the halon mass fraction in the tube reaches 100% at 0.4 seconds, when the halon is completely discharged from the vessel into the tube. For the larger tube, the halon mass fraction decreases more rapidly after the maximum than for the smaller tube. The discharging of the halon from the end of tube begins at 0.18 and 0.4 seconds, and the discharged halon mass fractions are 54.9 and 71.1% at 1 second for the 1 and 1.2 inch diameter tubes, respectively. These results represent that increasing the tube diameter is an effective way to enhance the amount discharged from the end of the tube, if the weight of the fire extinguishing system is not significant. Consequently, the rupture surface area and the tube volume should simultaneously be taken into account in order to design an optimal fire extinguishing system.

5. Conclusions

A numerical analysis of the flow characteristics was carried out, to facilitate optimal design of airplane fire extinguishing systems that use halon-1301 as a fire extinguishing agent. The unsteady flow model was simulated using the general-purpose software package "FLUENT", to investigate the flow characteristics of fire extinguishing agents in the system. The effects of the rupture surface area and tube diameter on the flow characteristics were studied. The time-dependent flows of the halon in the vessel and the tube were reported in this study.

A large amount of the halon remains in the vessel as the nitrogen gas enters the tube, so two-phase annular flow occurs in the tube.

The characteristics of the halon discharge from the tube end are very sensitive to the rupture surface area. As the rupture surface area decreases, a longer time elapses before the tube is filled with halon and before halon is discharged from the tube end, due to increased flow resistance. In the case of this study, there is a difference of 39.6% in the discharged mass fraction between rupture surface areas of 6/6 and 3/6.

The tube diameter significantly affects the characteristics of halon discharge from the tube end. The amount of halon discharged from the end of the tube increases as the tube diameter increases, even though the discharge through the tube end is retarded. The discharged halon mass fraction after 1 second increases from 54.9% to 71.1% when the tube diameter is increased from 1 inch to 1.2 inches. This confirms that increasing the tube diameter is an effective way to enhance the amount of halon discharged from the tube end. Consequently, the rupture surface area and the tube volume should simultaneously be taken into account in order to design an optimal fire extinguishing system.

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