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RAPID DISCHARGE OF A FIRE SUPPRESSING AGENT

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ABSTRACT

This paper describes an experimental method to study the rapid discharge of a fire suppressant (C_3F_8) from a pressurized vessel. Experimental observations inside and at the exit of the vessel were made using high-speed photography. Boiling was not observed inside the vessel during discharges. A simple mathematical model was developed to predict the liquid depletion level and is compared to the experimental measurements.

Introduction

Since the signing of the Montreal Protocol [1], extensive effort has been devoted to the search for halon alternative(s) to replace halon 1301 (CF_3Br), an ozone-depleting substance, as a fire suppressant. This study was a part of a comprehensive agent screening and performance evaluation program conducted at the National Institute of Standards and Technology (NIST) under the auspices of the U.S. Air Force, Navy, Army, and the Federal Aviation Administration in order to identify potential halon replacements for in-flight aircraft engine nacelle and dry bay fire protection. The engine nacelle is the portion of the airframe that houses the jet engines. Dry bays refer to normally closed spaces, often adjacent to flammable liquid storage tanks. A fire threat, which is unique to military aircraft, comes from the penetration of enemy anti-aircraft rounds into the dry bays during wartime

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missions. The time to detect and to suppress a dry bay fire is less than 100 ms. The work reported here is pertinent to dry bay applications.

In a conventional in-flight halon 1301 fire extinguisher bottle, a fixed amount of agent 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. Release of the agent from the vessel is normally achieved by a squib, either manually (with crew intervention) or automatically (for dry bay applications), upon the detection of a fire. A squib is an explosive device used to rupture a hermetical metal diaphragm so that rapid initiation of a flow through the ruptured diaphragm can be achieved.

Due to pressurization, nitrogen is dissolved into the liquid agent. The events occurring inside and outside of a pressurized vessel during discharge are very complicated due to the degassing of the dissolved nitrogen and the resulting two-phase flow. The discharge process consists of two major components: (1) the release of an agent and (2) the subsequent dispersion (mixing and evaporation) of the agent. The discharge process determines how an agent is delivered to a fire scene; the effectiveness of an agent in suppressing a fire depends on how it is transported to the fire. Since no prior work on rapid discharge of halon alternatives exists in the literature, the research effort at NIST was to examine the discharge characteristics of the alternative agents and to establish agent selection criteria based on discharge performance of these agents. This paper describes an experimental method to study the rapid release of a halon replacement from a pressurized vessel. The work reported here was designed to address the behavior of a proposed alternative agent inside the pressure vessel during *rapid* discharge and to obtain agent discharge rates. The characteristic discharge time is on the order of tens of milliseconds. Only the results for one of the potential halon alternatives, FC-218 (C_3F_8), are presented and discussed. The effects of dissolved nitrogen are not considered in this communication. The thermophysical properties of FC-218, the experimental results for several other potential halon alternatives, the effects of dissolved nitrogen and other experimental parameters on the discharge processes, and the agent dispersion characteristics can be found in the two recent NIST Special Publications [2,3].

Experimental Method

The experimental apparatus is shown in Figure 1. It consists of a pressure vessel, a dynamic pressure transducer to measure the pressure-time history inside the vessel during a discharge, a nitrogen supply bottle, a needle valve and a solenoid valve. The pressure vessel used in this study was made of clear acrylic plastic (polymethyl methacrylate), which enabled visualization of the internal behavior of the agents during discharge and the measurement of emptying rates of the agent from the vessel. The internal volume of the vessel was measured to be 5.09×10^{-4} m³. A stainless steel vessel was employed when experimental conditions did not require the use of the plastic vessel [2].

A scored rupture disc with a diameter of 9.1 mm was chosen as a quick release mechanism because the bursting of the disc is almost instantaneous once a specified pressure has been reached and a simple straight-through and full opening of the non-fragmented burst disc can be obtained. This technique had been successfully used previously in a study of rapid venting of hot, high pressure liquids from a pressure vessel [4,5]. The discs were
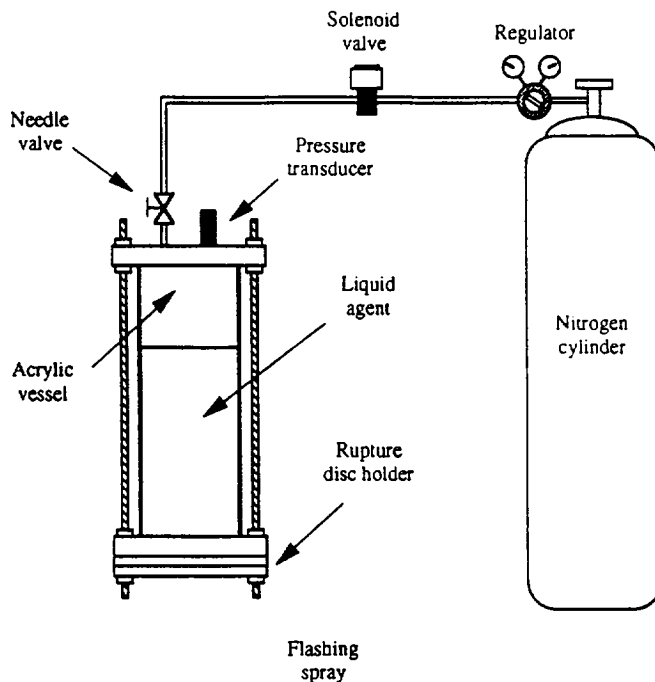
FIG. 1
Experimental apparatus.

made of stainless steel (SS 316) with a nominal burst pressure of 4.12 MPa at 22 °C. The actual burst pressure, in most cases, varied less than $\pm$ 10 % of the nominal burst pressure.

The experimental procedure involved the following steps. The vessel was first filled with liquid agent to approximately two-thirds by volume. The total mass of the agent dispensed to the vessel was obtained by weighing on an electronic scale with an accuracy of 1 g. The vessel was then pressurized with nitrogen to 75 % of the nominal burst pressure of the rupture disc through a solenoid valve and the needle valve. To initiate a discharge, the upstream nitrogen pressure in the nitrogen supply line was first raised to approximately 15 % above the nominal burst pressure with the solenoid valve closed. The solenoid valve was then opened to start a flow of nitrogen into the vessel through the needle valve and to initiate the experiment. The nitrogen flow continuously increased the internal pressure of the vessel to a point where the rupture disc could no longer sustain the rising internal pressure. Bursting and complete opening of the rupture disc followed, thus causing rapid discharge of the agent from the vessel. Experiments were conducted by discharging the liquid agent vertically downward at room temperature. The voltage from the pressure transducer was recorded using a high-speed 12-bit data acquisition board at a rate of 25 kHz and stored in a personal computer for subsequent data analysis.

A high-speed movie camera operating at 2000 frames per second was used to document the events occurring inside the plastic vessel. Intense front and back illumination was used. Emptying rates were obtained by using frame-by-frame analysis of the movies taken from the experiments. The high-speed motion picture film acquired for each discharge was analyzed using a slide scanner and digital image processing software. Emptying rates were extracted from the digitized images of the liquid level of the agent in the vessel as a function of time during discharge. The uncertainty in the liquid position measurements is typically $\pm$ 0.4 mm. The discussion of other experimental uncertainties can be found in [2].

Attempts to record temperatures in both phases (vapor and liquid) inside the vessel during discharges proved to be difficult although some qualitative information could still be obtained from the temperature measurements. The difficulty lies in the response time and the fragility of fine wire thermocouples. Even a fine 12 μm unsheathed thermocouple was found to have a time constant which was too long to follow the events occurring inside the vessel.

In an actual discharge, there is no continuous flow of nitrogen into the vessel. However, the present experimental design depends on the inflow of nitrogen to raise the internal pressure of the vessel above the rupture point of the disc. Furthermore, it was not possible to shut off the nitrogen flow to the vessel at the instant when the rupture disc burst due to the relatively slow response time (~ 35 ms) of the solenoid used to connect the vessel and nitrogen supply line. A series of experiments were performed to assess the effect of the continuous nitrogen inflow during discharge. It was found that by regulating the needle valve to minimize the inflow of nitrogen such that the duration from the initiation of nitrogen flow to the rupture of the burst disc was greater than one second, no appreciable differences (within the experimental uncertainty due to the actual burst pressure) were detected in the internal pressure traces during discharge. Therefore, it can be concluded that this continuous flow of nitrogen has an *insignificant* effect on the discharge behavior.

Results and Discussion

Visual observations of the events occurring inside the vessel during downward discharge are described as follows. Liquid agent is propelled out of the vessel when the rupture disc breaks. In some of the experiments, the inflow of nitrogen disturbs the liquid/vapor interface, causing a wavy motion along the liquid surface. Apparently these disturbances did not affect the agent release behavior. At the end of the liquid discharge the vessel interior becomes foggy, possibly due to the condensation of vapor caused by a decrease in temperature in the ullage because of the expansion of the vapor phase. As the discharge of the remaining vapor continues, the vessel becomes clear once again. A photographic sequence of events during a downward discharge of FC-218 from a plastic vessel is illustrated in Figure 2. The dark grey horizontal shadow in the middle of the background was caused by the back illumination. The first photograph shows the transparent plastic vessel, the vessel mount, and the liquid level. In this sequence of photographs, the perturbation of the vapor/liquid interface caused by the inflow of nitrogen is evident from the wavy nature of the interface. The photographs also show the flashing behavior of the fire suppressing agent outside the vessel during discharge.
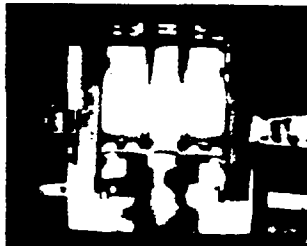
Figure 3 shows the temporal variation of the internal pressure during a discharge. Pressures reported in the figure are gauge pressures. The pressure is nondimensionalized by the actual burst pressure, P_i, which is taken to
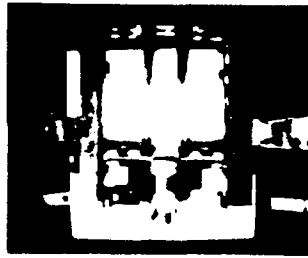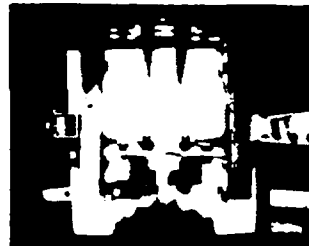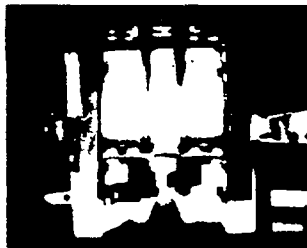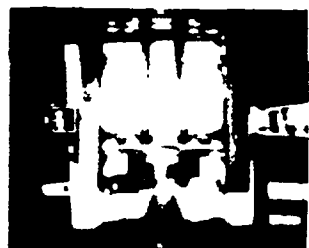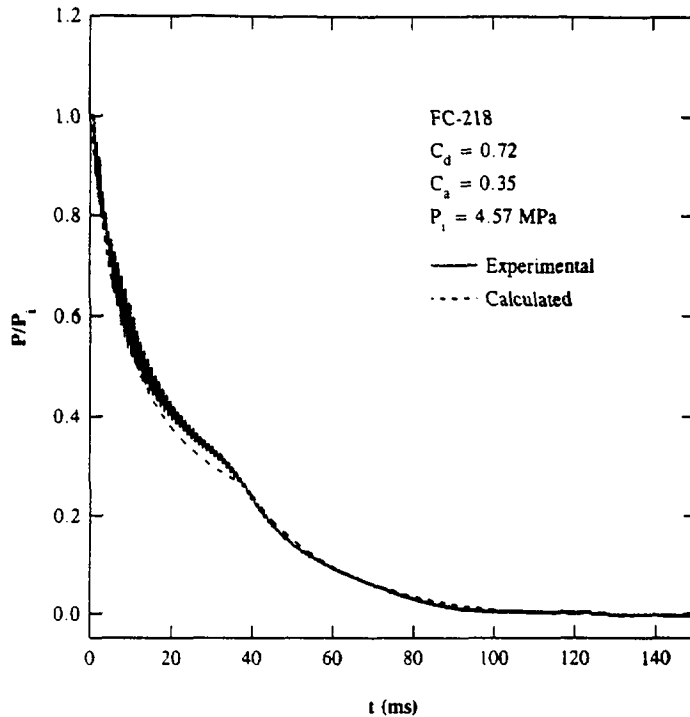
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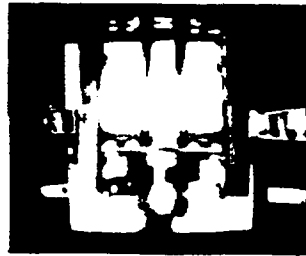
1.0 ms

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FIG. 2
A photographic sequence showing a discharge of FC-218.

FIG. 3
Comparison of measured pressure-time history of a FC-218 discharge with prediction.

be the pressure at $t = 0$. There are two distinct regions, separated by an inflection point, in the pressure-time history. The first region corresponds to the time interval during which the liquid agent is being propelled from the vessel; the second region corresponds to the duration when the remaining vapor (mostly nitrogen) is being vented from the vessel. Based on the experimental observations, the inflection point corresponds very closely to the time at which the liquid agent has just been completely expelled from the vessel. The measured pressure-time history has an oscillatory nature and is noisy. This behavior was caused by vibration of the vessel mount during discharge.

The visual observation of the internal behavior of liquid agent during discharge from plastic vessels shows that during the time when the liquid level is visible (refer to Figure 2) no internal boiling of the liquid occurs during depressurization. This observation can be explained by examining the temporal variation of the internal pressure. For FC-218 with a normal boiling point of -36.8 °C, the pressure at the time when the liquid empties (at the inflection point in the pressure-time history) is still well above the vapor pressure of FC-218 at room temperature (0.88 MPa at 25 °C). Although the temperature of the ullage above the liquid is very low because of the expansion of the vapor phase, the liquid agent remains at the initial room temperature and can be considered to undergo an isothermal depressurization during discharge [2].

Based on visual observations of the discharges, a simple mathematical model can be formulated to simulate the pressure-time history. As mentioned above, there are two distinct regions, separated by an inflection point, in the pressure-time traces. The first region corresponds to the liquid discharge while the second region corresponds to the discharge of the remaining vapor after the liquid has been released from the vessel. The formulation of the model for liquid discharge will first be presented, followed by a discussion of the simulation of the discharge process of the remaining vapor.

Once the rupture disc bursts, the nitrogen above the liquid agent simply acts as a piston to drive the liquid out of the vessel. The control volume that is being considered is the ullage above the liquid. Since the discharge process is very rapid, the process occurring in the gas phase can be assumed to be adiabatic and reversible, *i.e.*, isentropic. Furthermore, for simplicity the control volume is assumed to be closed in the analysis because the inflow of nitrogen does not appear to influence the discharge process. Assuming the vapor phase to be ideal, from the first law of thermodynamics for an isentropic process,

$$PV^\gamma = constant \; , \tag{1}$$

Since nitrogen is the dominant species in the vapor phase, the γ of nitrogen with a value of 1.4 is assumed. If a time derivative of Equation (1) is taken, then

$$\frac{dP}{dt} + \frac{P\gamma}{V}\frac{dV}{dt} = 0 \; . \tag{2}$$

Because of the design of the rupture disc holder, there is a short distance, L (25.4 mm), through which the fluid has to pass before exiting from the release vessel assembly. Due to rapid depressurization, the liquid becomes superheated as it passes through the opening of the disc [6]. Superheating of the liquid has been observed in previous studies on the discharge of saturated and subcooled liquid from orifices and nozzles [7-14]. If we assume that the flow of metastable liquid through the disc opening (D) and the disc holder can be approximated by flow through a short tube ($0 < L/D < 3$), then the volumetric flow of the liquid, expressed in terms of the volumetric expansion rate of the gas above the liquid agent, can be calculated by [12,15]

$$\frac{dV}{dt} = C_d A \sqrt{\frac{2(P - P_{sat})}{\rho_l}} \; , \tag{3}$$

Measured values for C_d were found to be between 0.61 to 0.64 in the literature [12,15]. Equations (2) and (3) were solved numerically by using a fourth order Runge-Kutta method [16] to obtain the pressure-time histories and the liquid level as a function of time.

Figure 4 shows the temporal variations of liquid level for FC-218 obtained from a run using a plastic vessel. Also shown in the figure are predictions obtained using Equations (2) and (3). Since the liquid levels were measured with respect to a reference point, a zero liquid level does not correspond to complete depletion of liquid. The best fit curve was obtained by optimizing the values of C_d, which varied between 0.60 to 0.72 for all the FC-218 tests. The C_d values are slightly higher than previous experimental values reported in the literature [12,15].
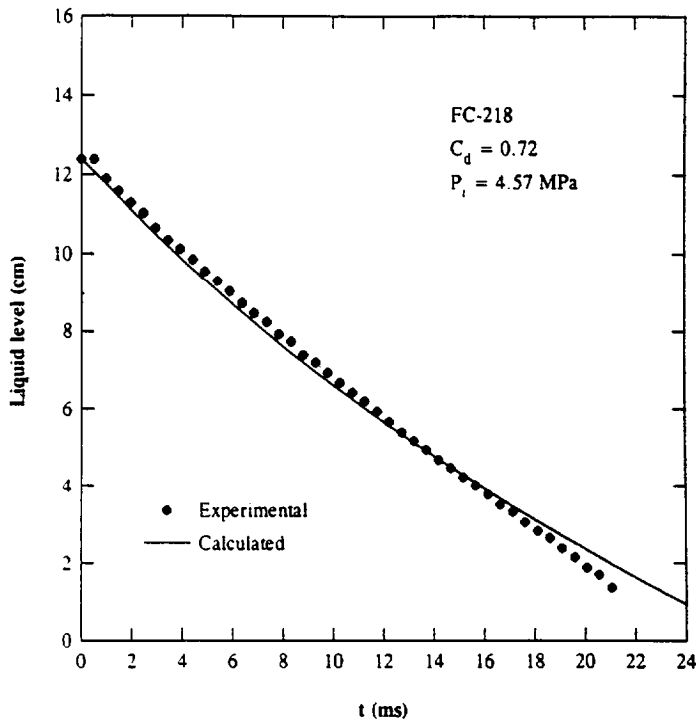
FIG. 4
Temporal variation of liquid level obtained from a FC-218 discharge.

Despite the simplicity of the model, the agreement between measured and predicted liquid depletion levels is quite remarkable. However, in all cases, over-predictions were noted at later discharge times. It was conjectured that the over-predictions were caused by the entrance effect as the depleting liquid level became closer and closer to the opening of the rupture disc.

After complete depletion of liquid, the discharge process of the remaining vapor can be modeled as follows. If the vapor is assumed to be an ideal gas, the process is again assumed to be isentropic, and the pressure in the vessel is high enough that the flow can be assumed to be choked in the disc opening (which is approximated as a round, sharp-edged orifice), it can be easily shown that the following equation describes the rate of pressure decay in a vessel as a function of time [4].

$$\frac{P}{P_{el}} = \left[1 - \frac{C_a A}{V} \left(\frac{R T_{el} \gamma^3 K}{M} \right)^{1/2} \left(\frac{1 - \gamma}{2 \gamma} \right) t \right]^{\frac{2\gamma}{1 - \gamma}} , \qquad (4)$$

with

$$K = \left(\frac{2}{\gamma + 1}\right)^{\left(\frac{\gamma + 1}{\gamma - 1}\right)} , \tag{5}$$

A choked flow is justifiable because P_e/P is less than the critical pressure ratio most of the time during discharge of the remaining vapor. The value for C_d normally centers around 0.6 [17].

Figure 3 also compares the complete pressure-time histories with predictions from Equations (2), (3), (4), and (5). The best fit curve for the duration of vapor discharge was obtained by optimizing the value of C_a. This value is lower than the value quoted in the literature [17]. However, instead of using the P_{ei}'s from the liquid discharge calculations, if one fits the experimental results of vapor discharge by optimizing both P_{ei} and C_a, the value of C_d is found to be ~ 0.6.

Conclusions

The rapid discharge of a fire suppressing agent (FC-218) was examined experimentally. No boiling inside the vessel was observed during downward discharges. A simple analysis based on an isentropic process and superheated liquid agent discharge predicted the pressure-time history inside the vessel and the liquid depletion level quite well.

Acknowledgments

Nomenclature

A	Cross sectional area of the disc opening, m^2
C_a	Discharge coefficient for the gas, dimensionless
C_d	Discharge coefficient for the superheated liquid, dimensionless
D	Diameter of the disc opening, m
K	Defined in Equation (5), dimensionless
L	Short distance, m
M	Molecular weight of vapor (assumed to be nitrogen), kg/mole
P	Pressure, MPa
P_e	Exit pressure, MPa
P_d	Pressure in the vessel at the instant of complete depletion of liquid, MPa
P_i	Actual burst pressure of the rupture disc, MPa
P_{sa}	Vapor pressure of the agent, MPa
R	Universal gas constant, Pa m^3 mol^{-1} K^{-1}
T_d	Temperature in the vessel at the instant of complete depletion of liquid, K
V	Volume, m^3
t	Time, ms

γ Ratio of the constant pressure and volume heat capacities, dimensionless

ρ_l Liquid agent density, kg/m^3

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