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DISCHARGE CHARACTERISTICS OF CRYOGENIC FLUIDS FROM A PRESSURIZED VESSEL

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ABSTRACT

An experimental technique to study the rapid release of liquid cryogenic fluids from a pressurized vessel orientated downward is described. A rupture disc was used as the release mechanism. Experimental observations were made on the discharge characteristics of two cryogenic fluids, C_4F_{10} (FC-31-10) and C_3F_8 (FC-218), which were proposed as potential candidates for replacement of halon 1301 (CF_3Br) as fire suppressant. For comparison, halon 1301 was also included in this study. Various parameters that could influence the discharge process were studied. These parameters were: (1) orifice opening, (2) the effect of an extension tube at the vessel exit, and (3) initial charge pressure. The events occurring internal and external to the vessel during discharge of FC-31-10 or FC-218 were studied with high-speed photography and a transparent acrylic vessel. The average penetration velocities of the spray at various locations downstream were measured by means of a laser extinction technique. Two distinct flashing behaviors were observed at the vessel exit. The first flashing occurred immediately after the bursting of the rupture disc, and the second appeared at or before the moment the liquid was depleted from the vessel. During depressurization, no internal boiling of FC-31-10 or FC-218 was observed. Increasing the initial charge pressure reduced the emptying time of the liquid. Decreasing the orifice opening was found to increase the liquid emptying time significantly. The behavior of the liquid inside the vessel was found to be very similar whether an extension tube was present or absent at the vessel exit: an indication of two-phase critical flow.

INTRODUCTION

The signing of the Montreal Protocol has accelerated the search for halon alternatives. This study constitutes part of a comprehensive program, sponsored by the U.S. Air Force/Navy/Army/Federal Aviation Administration and currently conducted at the National Institute of Standards and Technology, to identify alternatives to halon 1301 (CF_3Br) for in-flight aircraft fire protection. Eleven agents, ranging from perfluorocarbons (FC's), hydrofluorocarbons (HFC's), and hydrochloroflurocarbons (HCFC's), have been proposed. They are $CF_3CH_2CF_3$, C_4F_{10}, cyclo-C_4F_8, CF_3CHClF, CF_3CHFCF_3, CH_2FCF_3, C_3F_8, CHF_2Cl, C_2HF_5, C_2HF_5 (40% by mass)/CH_2F_2 (60%) mixture, and C_2F_6.

Depending upon their applications, existing halon 1301 bottles are normally filled to about half of the bottle volume, and the bottle is then pressurized with nitrogen to 4.1 MPa. Discharge of the agent is normally accomplished by either manually or automatically activating a solenoid valve or a squib upon the detection of a fire. For fire protection of dry bays of a military aircraft, the agent has to be released from the vessel and suppress the fire in less than fifty milliseconds.

The events occurring inside and outside of a pressurized vessel containing alternative agent during rapid discharge can be extremely complicated due to the presence of a two-phase flashing flow. The importance of studying the discharge process stems from the fact that how effective an agent works in a fire depends partly on how the agent is discharged and delivered to the fire scene.

The main objective of this study is to characterize the discharge dynamics of alternative agents from a simulated fire extinguisher bottle and to characterize various parameters that would have a direct influence on the discharge process. In particular, the effect of orifice size, initial charging pressure, and an extension tube connected to the vessel were examined.

To study the various parameters on the discharge process, two representative alternative agents, C_4F_{10} (FC-31-10) and C_3F_8 (FC-218) and CF_3Br were selected among others because they represented the range of boiling points (-1.5 °C to -78.2 °C) encompassed by most of the eleven proposed fluids, and CF_3Br was included as a baseline agent for comparison. The boiling points of these three agents are -2.0 °C, -36.8 °C, and -57.8 °C respectively.

EXPERIMENTAL APPARATUS AND PROCEDURE

The pressure vessel used in this study is made of either stainless steel or clear acrylic plastic. The plastic vessel was used for visualizing the internal behavior of the agents during discharge and for obtaining emptying rates of the agents.

The stainless steel vessel has an internal diameter of 5.08 cm and a wall thickness of 0.64 cm. There are four access holes on top of the vessel for mounting a piezoelectric dynamic pressure transducer, two thermocouples, and a needle valve for dispensing the fluid into the vessel and for subsequent nitrogen pressurization. The other end of the vessel has a welded flange with an O-ring seal for mounting a rupture disc holder (see Fig. 1).

The plastic vessel is constructed from a clear acrylic plastic tube with an internal diameter of 5.08 cm and a wall thickness of 0.95 cm. The tube is sandwiched between two aluminum plates with O-ring seals by using four threaded rods. The rupture disc holder is attached to the bottom plate, whereas two access holes for mounting a dynamic pressure transducer and a needle valve are located on the top plate.

A rupture disc with a diameter of 19 mm was used as a rapid release mechanism for discharging an agent from the vessel. The disc is made of stainless steel with a nominal burst pressure of 4.1 MPa at 22 °C. The actual burst pressures, in most cases, varied less than $\pm$ 10% of the nominal burst pressure. A rupture disc 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 has been used in the study of rapid venting of hot, high pressure liquids from a pressure vessel [1].

A high-speed movie camera operating at 2000 frames per second with intense backlighting was used to document the events occurring inside and outside the vessel. Emptying rates were obtained by using frame-by-frame analysis of the movies taken from the experiments. Emptying rates were extracted from the depleting liquid level of the agent in the vessel during discharge.

In order to measure the flashing intensity of the spray, a dynamic pressure transducer was mounted at the exit of the vessel at a distance of 4.5 cm away from the centerline of the exit. The average penetrating velocities of the spray were measured by extinction of a series of five low power He/Ne lasers at various locations downstream of the vessel exit. Average velocities were calculated based on the extinction time and the distance between two adjacent lasers. A schematic diagram of the experimental apparatus is given in Fig. 1.

The experimental procedure involves the following steps. The vessel was evacuated for at least fifteen minutes, then connected to the agent supply bottle, and filled with liquid agent to approximately two-third full (by volume). The total mass of the agent was obtained by weighing on an electronic scale with an accuracy of $\pm$ 1 g. The vessel was then pressurized with nitrogen to 75% of the nominal burst pressure of the rupture disc through a solenoid valve located upstream of the needle valve. To initiate a discharge, the upstream nitrogen pressure in the solenoid valve was first raised to approximately 15% above the nominal burst pressure. The solenoid valve was then opened to start a flow of nitrogen into the vessel through the needle valve. The nitrogen flow continuously caused the internal pressure of the vessel to rise to a point where the rupture disc could no longer sustain the internal pressure. Bursting of the rupture disc thus allowed rapid release of the fluid from the vessel. The outputs from the pressure transducers, thermocouples, and detectors of the lasers were recorded by using a high-speed data acquisition board at a rate of 25 kHz and stored in a PC for subsequent data analysis.

Unless specified, discharge experiments were conducted by discharging vertically downward at room temperature with 4.1 MPa rupture discs. This condition will be referred to as standard discharge in the discussion.

The effect of the size of the opening on the discharge process was accessed by mounting various diameter orifice plates to restrict the opening of the rupture disc at the exit of the disc holder. The orifice diameters used in this study were 12.7 mm and 6.4 mm.

In order to simulate discharge through a pipe for engine nacelle fire protection applications, experiments were also performed using an extension tube 0.5 m long with an internal diameter equal to that of the rupture disc. The tube was attached to the vessel exit.

The effect of the initial charge pressure on the discharge was simulated and studied by performing a series of experiments using rupture discs with different burst pressures. Rupture discs with nominal burst pressure of 2.7 MPa and 5.5 MPa were selected.

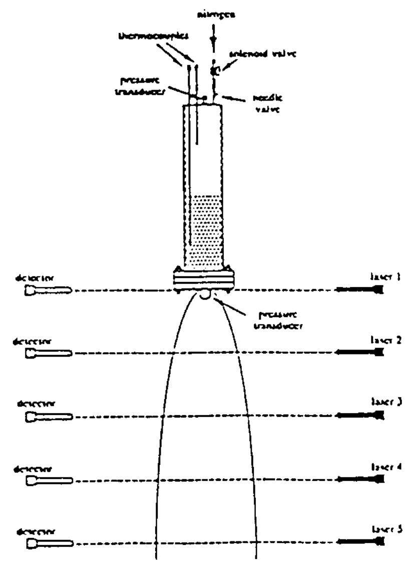

Fig. 1 Schematic of the experimental set-up

RESULTS AND DISCUSSION

Phenomenological Description. Visual observation of the event occurring inside the vessel during discharge is described as follows. Flashing occurs immediately after the bursting of the rupture disc. Liquid agent is then propelled out of the vessel by the high pressure vapor in the vessel above it. For FC-31-10, a metastable superheated liquid core is clearly visible at the vessel exit. In some of the experiments, the inflow of nitrogen disturbs the liquid/vapor interface causing a wavy motion along the liquid surface. A second flashing is observed to occur at or before the moment when the liquid is completely depleted. At the end of the liquid discharge, the vessel becomes foggy with vapor condensate possibly from temperature decrease in the ullage due to vapor phase expansion. As the discharge of the remaining vapor continues, the vessel becomes clear again.

Standard Discharge. Fig. 2 shows the results of temporal variation of the internal pressure during downward discharge of FC-218 from a plastic vessel using rupture discs with nominal burst pressure of 4.1 MPa. Fig. 2 also shows the repeatability of the experiment. The variations in the pressure-time histories from run to run reflect the nature of the rupture disc, that is, the actual burst pressure of each rupture disc used in the experiments deviated somewhat from the nominal burst pressure from run to run. Similar trends were observed for FC-31-10. The pressure is nondimensionalized by the actual burst pressure, P_i, which is taken to 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 is being discharged from the vessel; the second region corresponds to the duration when the remaining vapor is being vented from the vessel. Based on the observations from the plastic vessel experiments, the inflection point corresponds very closely to the time at which the liquid agent has just been completely depleted from the vessel.

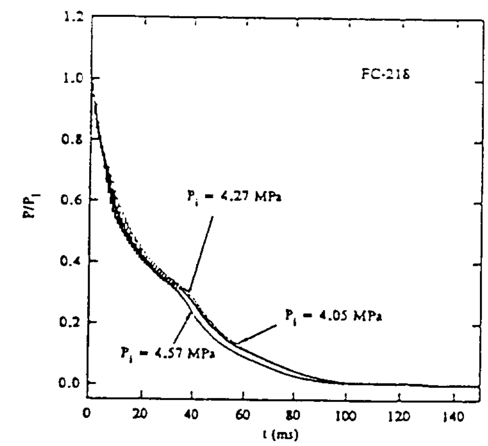

Fig. 2 Temporal variations of the internal pressure during discharges of FC-218

The visual observation of the internal behavior of liquid FC-218 or FC-31-10 during discharge from plastic vessels shows that no internal boiling of the liquid occurs during depressurization. This observation can be explained by examining the temporal variation of the internal pressure. From Fig. 2, the pressure when the liquid empties (at the inflection point in the pressure-time history) remains above the saturation vapor pressure of the agent at room temperature. Note that the liquid temperature remains at room temperature during discharge although the temperature of the ullage above the liquid is very low because of the expansion of the vapor phase, the reason being that the characteristic time for the interfacial heat transfer between the liquid and the vapor phase is much longer than the discharge time of the liquid.

Fig. 3 shows the results of CF_3Br discharging from the stainless steel vessel. The pressure-time trace is much smoother compared to those obtained using the plastic vessel. The oscillatory behavior in the pressure-time traces from the plastic experiments was due to the vibration of the mount for the plastic vessel during discharge. The plastic vessel was not used for observing the internal behavior of the liquid during discharge for fear of explosion of the vessel during vessel filling and handling because CF_3Br has a relatively high vapor pressure (1.43 MPa) at 20 °C. The pressure-time histories show that the transition from the liquid discharge to the venting of the remaining vapor from the vessel is not distinct and abrupt, but appears to be gradual. Because the internal pressure at the vicinity of the transition is below the saturation vapor pressure of the agent, it is conjectured that boiling of the liquid might have occurred close to the end of the liquid discharge thus causing a gradual transition rather than an abrupt change in the pressure-time histories.

The results of the average velocities of the penetrating spray are summarized in Fig. 4 for all three fluids. In the case of FC-31-10, the spray front tends to accelerate slightly. For FC-218 and CF_3Br, the spray front decelerates rapidly downstream.

The flashing behavior at the vessel exit is shown in Fig. 5. For FC-31-10, the first flash at the instant when the rupture disc breaks is so weak that the pressure rise can not be detected. For FC-218 and CF_3Br, the first flash is clearly visible in the pressure traces. The second flash corresponds to the second pressure surge in the figure. Note that for

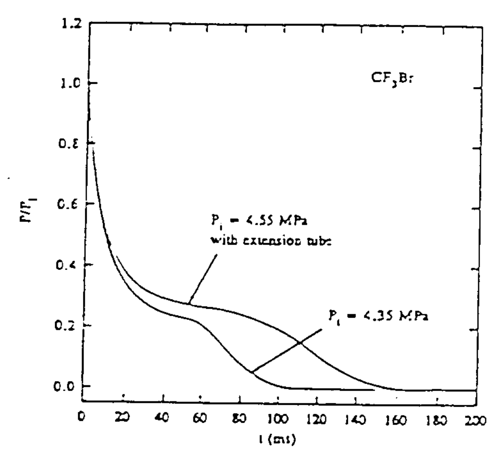

Fig. 3 Temporal variations of the internal pressure during discharges of CF_3Br with and without an extension tube

CF_3Br, continuous flashing behavior at the vessel exit persists after the first flash although a second strong flash is also noticeable in the figure.

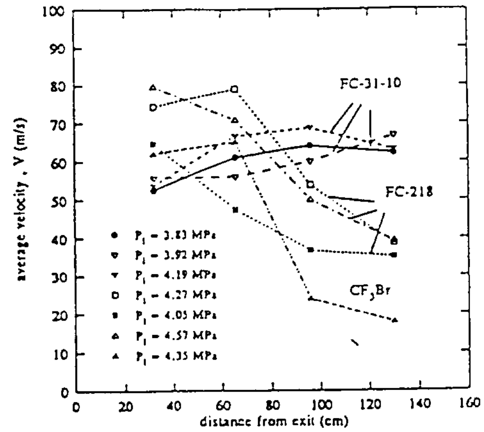

Fig. 4 Average velocities of the penetrating spray

Effect of Orifice Plate. The experimental results obtained by restricting the disc opening by means of an orifice plate are shown in Fig. 6 for FC-31-10. Based on visual observation, there is no difference in the internal behavior of the liquid agent. The discharge process is very similar to that without the orifice plate. The only noticeable effect of the orifice plate on the discharge process is to increase the emptying time of the liquid, as indicated by the locations of the inflection points in Fig. 6. Similar trends were observed for FC-218 and CF_3Br.

Figs. 7 and 8 summarize the flashing behavior of the three fluids during discharge in the presence of a restricting orifice plate at the vessel exit. From visual observation, the external flashing behavior is also very similar with or without the orifice plate at the vessel exit although the pressure rise concomitant with the flashing was not detected in the cases of FC-31-10 and FC-218 when a 6.4 mm plate was used. The average velocities of the penetrating spray, as shown in Figs. 9 and 10, were found to decelerate rapidly downstream for all three agents when a orifice plate was placed at the vessel exit.

Effect of an Extension Tube. The presence of an extension tube at the vessel exit was observed not to have an effect on the internal behavior of the liquid during discharge. Fig. 11 shows the experimental results of FC-31-10. For comparison, the results obtained with no extension tube are also shown in the figure. It appears that the presence of an extension tube does not change the temporal behavior of the internal pressure during the discharge of the liquid. This is indicative of the existence of critical flow since the downstream geometry does not affect the pressure upstream [2]. Similar behavior was observed for FC-218. Note that the effect of an extension tube on the discharge of CF_3Br is apparent in Fig. 3. This could be the result of the internal boiling of the liquid as suggested in the above discussion. The average velocities of the jet downstream of the exit of the tube were measured to be much higher than those without the tube. In some cases, average velocities of 170 m/s or higher were recorded.

Effect of Initial Pressure. Fig. 12 shows the pressure-time histories for FC-218 based on three initial pressures. The results for P_i = 6.18 MPa were obtained using the stainless steel vessel. It is clear that the emptying time of the liquid decreases with increasing initial pressure in the vessel.
As shown in Fig. 13, the flashing behavior is very similar to the case of standard discharge. The second flash happens sooner for higher initial pressure. This is not surprising because the liquid empties faster. The average velocities of the penetrating spray were measured to be higher when a higher initial pressure was used, as summarized in Fig. 14.

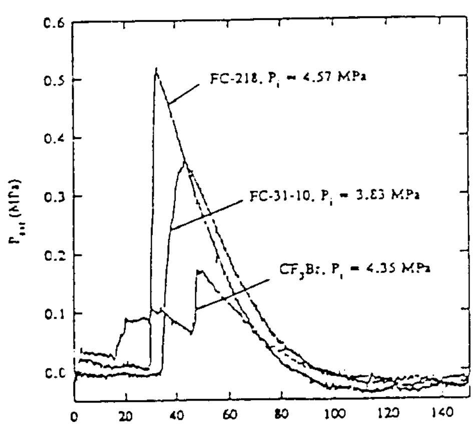

Fig. 5 Temporal variations of the external pressure measured at the vessel exit at a distance 4.5 cm away from the centerline of the exit

CONCLUSIONS.

In downward discharge, two distinct regions in the pressure-time histories are noted for FC-31-10 and FC-218 although the distinction is not as clear for CF_3Br. The first region represents the interval during which the liquid is being discharged; the second region corresponds to the discharge of the remaining vapor. No internal boiling is observed for FC-31-10 and FC-218. The pressure-time histories of CF_3Br, however, suggest internal boiling of CF_3Br might have occurred near the end of liquid discharge. Two flashing behaviors are observed at the vessel exit. The first flashing occurs immediately after the bursting of the rupture disc, and the second appeared to occur at or before the moment when the liquid was depleted from the vessel. The effect of a restricting orifice plate at the vessel exit is to increase the liquid emptying time and to decrease rapidly downstream velocity. The behavior of the liquid inside the vessel is very similar whether an extension tube is present or absent at the vessel exit. Increasing the initial discharge pressure decreases the emptying time of the liquid.

NOMENCLATURE

P	internal pressure of the vessel (MPa)
P_i	actual burst pressure at which the rupture disc breaks (MPa)
P_{ext}	pressure at the vessel exit (MPa)
t	time (s)
V	average velocity (m/s)

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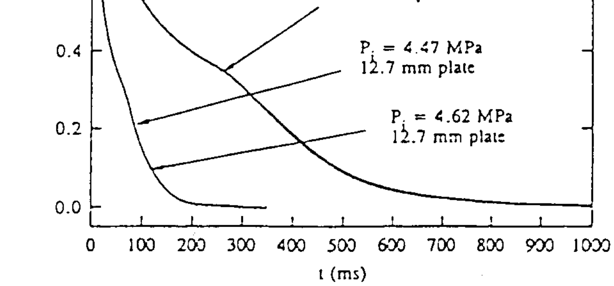

Fig. 6 Temporal variations of internal pressure during discharges of FC-31-10 with a restricting orifice plate

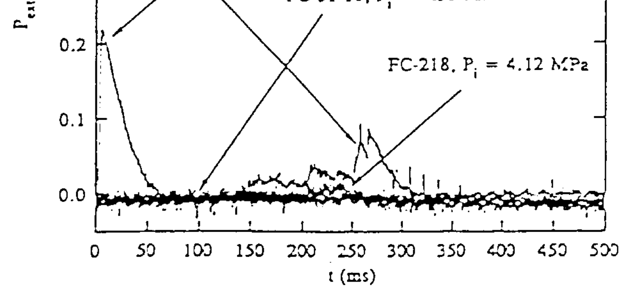

Fig. 7 Temporal variations of the external pressure measured at the vessel exit (with a 6.4 mm orifice) at a distance 4.5 cm away from the centerline of the exit

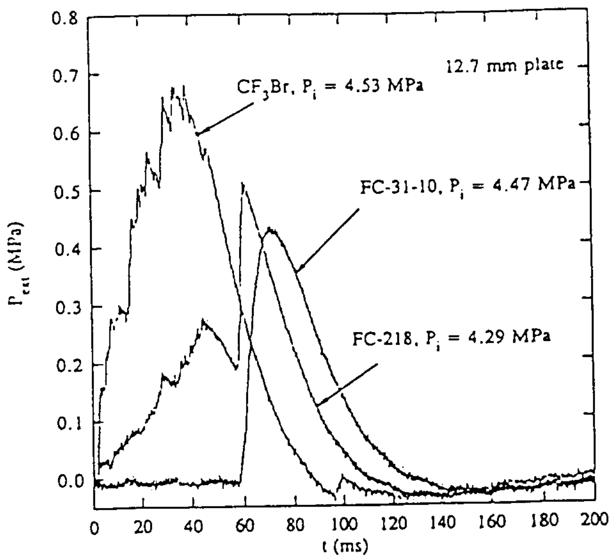

Fig. 8 Temporal variations of the external pressure measured at the vessel exit (with a 12.7 mm orifice) at a distance 4.5 cm away from the centerline of the exit

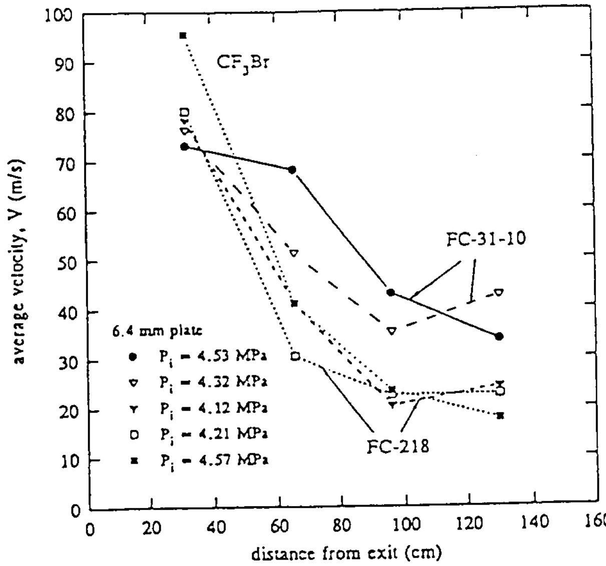

Fig. 9 Average velocities of the penetrating spray with a 6.4 mm orifice at the vessel exit

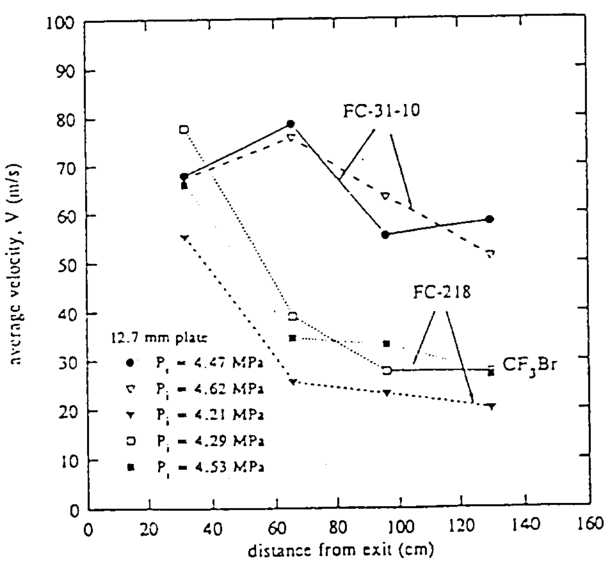

Fig. 10 Average velocities of the penetrating spray with a 12.7 mm orifice at the vessel exit

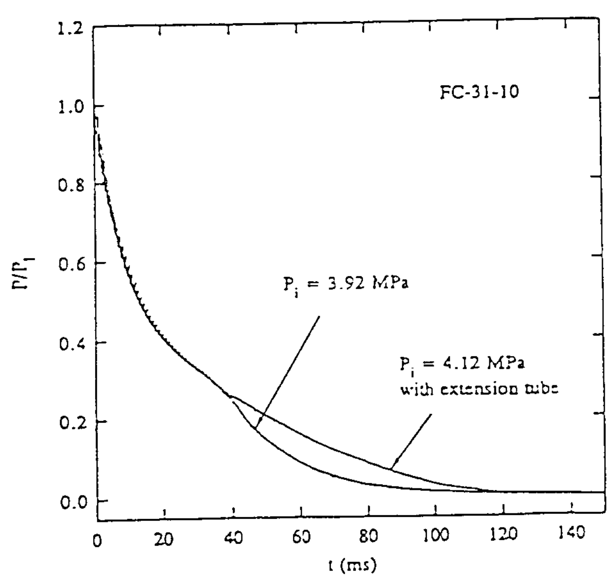

Fig. 11 Temporal variations of the internal pressure during discharges of FC-31-10 with and without an extension tube

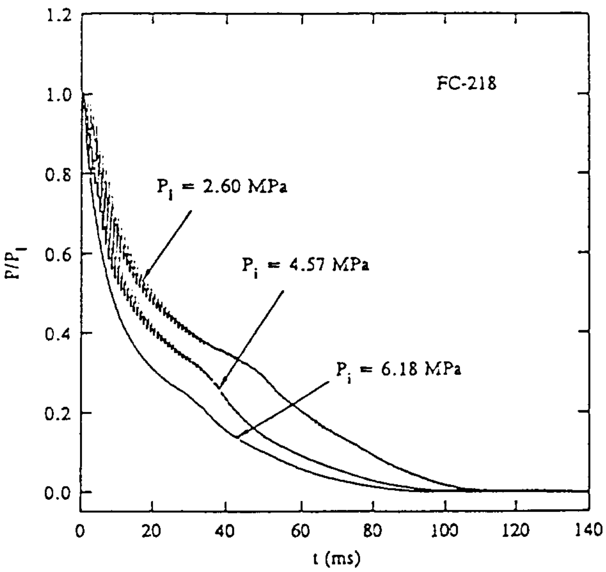

Fig. 12 Temporal variations of the internal pressure during discharges of FC-218 with different initial burst pressures

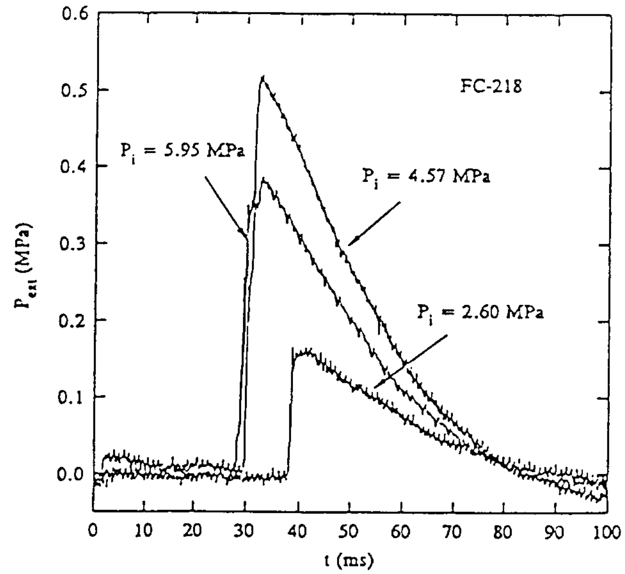

Fig. 13 Temporal variations of the external pressure measured at the vessel exit at a distance 4.5 cm away from the centerline of the exit with different initial burst pressures

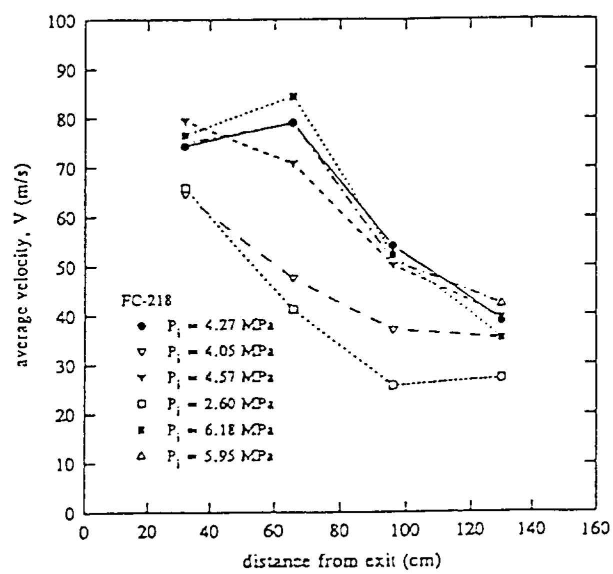

Fig. 14 Average velocities of the penetrating spray with different initial burst pressures