

Pipe Flow Characteristics of Alternative Agents for Engine Nacelle Fire Protection

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ABSTRACT

As part of the U.S. Air Force, Army, Navy and FAA Halon Replacement Project at NIST, the pipe flow characteristics were investigated for three engine nacelle alternative candidates: HFC-227ea, HFC-125 and CF_3I . The flow regime in suppression system piping is characteristically a two-phase, two-component gas/liquid system. **An** apparatus was built to study the pressure drop and flow time of the alternative agents and of halon 1301 as a reference for different storage conditions and piping configurations. The pressure drops and flow times of the alternative agents and halon 1301 show similar trends suggesting that for actual systems, design approaches similar to those used for halon 1301 systems are possible for the alternatives. High speed movies confirmed the two-phase nature of the flow. **A** computer model that simulates steady-state and transient discharge of nitrogen-pressurized agent from a storage bottle through piping was developed. The model may prove useful in preliminary design of engine nacelle systems employing an alternative agent.

INTRODUCTION

U.S. military and commercial aircraft jet engine nacelle fire protection has relied on halon 1301 fire suppression systems for a number of years. The phase-out of the halons due to environmental concerns necessitates the selection of a replacement agent. Previous work identified potential replacements for halon 1301 (Grosshandler *et al.*, 1994), while the work here focuses on the performance of alternative agents based on transport time through piping. It is desirable to discharge the agent into the nacelle quickly in order to achieve high agent concentrations and promote mixing. Design parameters such as pipe diameter, length, and storage conditions (agent and nitrogen amounts and ambient temperature) play a significant role in the system's discharge performance. The effects of storage bottle fill conditions, bottle temperature and piping configuration were explored.

A storage bottle contains agent, most of it in a liquid form, superpressurized with nitrogen. **An** actual system discharge exhibits highly transient flow behavior. At first, **as** the pipe is filling with agent, the pipe pressure at any point is rising rapidly while the bottle pressure is falling rapidly. The pipe pressure achieves a maximum when the pipe just fills, then **starts** to fall along with the bottle pressure. As the bottle pressure drops, nitrogen dissolved in the liquid phase may not come out of solution immediately, resulting in a meta-stable, supersaturated solution. After some time delay, degassing of the dissolved nitrogen **can** produce a net pressure rise inside the bottle due to the expansion of a bubbly two-phase fluid. The bottle pressure may reach a local maximum then start to drop again **as** this two-phase fluid continues to empty. **At** the point where the last of the two-phase fluid is being expelled from the bottle, a pressure rise is observed in the piping for a short period of time. The fluid in the piping is changing from a low quality (mostly liquid) fluid to a high quality (mostly gaseous)

fluid, which exhibits a different pressure drop in the piping. At that point, most of the agent has been discharged from the bottle and piping. The pressure in the piping starts dropping again as the ullage contents discharge. The two-phase fluid is compressible; thus it is possible to exhibit choking. In gaseous flows, choking is the realization of a thermodynamic limit on the mass flux as the flow achieves its sonic velocity; critical flow and choked flow have the same meaning. In two-phase gas/liquid flows choking may be realized at velocities below that of the gas-phase sonic velocity. If the flow is choked, the mass flow rate is independent of the discharge pressure (here, the pressure of the ambience).

There are three calculation methods for halon 1301 pipe flow described in the literature. The National Fire Protection Association's Standard 12A "Halon 1301 Fire Extinguishing Systems" (1993) gives a simplified design calculation for systems that should meet the performance criteria for extended discharge into enclosed spaces. The pipe flow equation is an application of the steady-state mechanical energy and mass balances with a specified friction factor and data specific to halon 1301 inserted; homogeneous, equilibrium two-phase flow is assumed. Pipe flow calculations are based on a fixed average bottle pressure condition and adiabatic, isenthalpic flow. This method was designed for extended discharges (discharge times of about 10 s). Elliot *et al.* (1984) used a homogeneous, equilibrium model of two-phase flow to solve for transient pipe and nozzle flow in halon systems. They also examined a Los Alamos National Laboratory code "Sola-Loop," developed for the steam/water system, to predict the transient discharge of halon. Both of their calculations compare favorably to some limited halon 1301 pipe flow tests.

These documented flow calculations do well for certain situations, but rely on data explicit to halon 1301, and make various assumptions about the flow. The observations and data from this study verify some of the assumptions, and their validity for the alternative agents. Here, a model that simulates the transient discharge of an agent through piping has been developed. It is similar to the NFPA 12A methodology and Elliot's model in that it is based on a homogeneous, equilibrium two-phase flow description. Thermodynamic properties and fill conditions are obtained from a separate vapor-liquid equilibrium computer program (Yang *et al.*, 1995).

EXPERIMENTAL METHOD

The pipe flow apparatus was designed so that different configurations and conditions could be studied. A schematic diagram of the apparatus is shown in Figure 1 and each of its major components is described below. Pipe diameters and lengths were selected based on a review of military aircraft specifications. Also, the bottle fill condition and nitrogen pressurization were selected based on knowledge of typical halon 1301 engine nacelle systems.

The storage vessel was constructed from a cylindrical tube of stainless steel with an internal diameter of 100 mm. The vessel internal volume was $4.06 \times 10^{-3} \pm 0.01 \times 10^{-3} \text{ m}^3$. This volume was verified by water displacement. The nitrogen make-up tanks were two standard high-pressure gas cylinders with a combined internal volume of $88 \times 10^{-3} \text{ m}^3$. A large orifice valve was used to deliver the make-up nitrogen to the storage vessel. The agent release mechanism was a quick-opening solenoid valve (Marotta Scientific Controls Inc.¹) with an inlet diameter of 31.8 mm and an exit diameter of 44.5 mm. The valve exit is at a 90° angle to the inlet. The opening time was on the order of 10 ms. Since the valve exit was much larger than the internal pipe diameters used in this study, a smooth tapered connector was fabricated to make the internal diameter transition from 44.5

¹Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

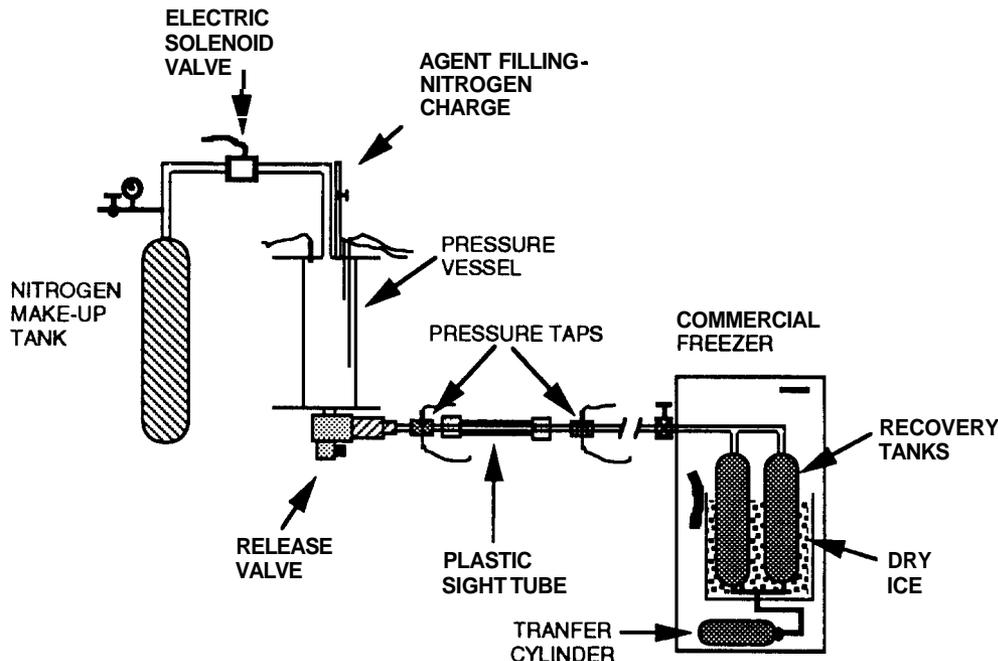


Figure 1. Schematic of the pipe flow apparatus.

mm to **15.9 mm**. The piping was drawn stainless steel tubing and two internal diameters were investigated, **15.9 mm** and **9.5 mm**. Brass pressure taps were constructed with the same inner diameter as each of the pipes which allowed the pipe pressure transducers to be installed flush to the tube wall in the horizontal orientation. The piping sections were connected with threaded fittings for easy reconfiguration, and rigidly attached to a bench to limit motion during agent discharge. The recovery tanks contained the agent after it flowed through the piping. They consisted of four separate high pressure sample cylinders with a combined internal volume of **$15 \times 10^{-3} \text{ m}^3$** , located in a commercial freezer and surrounded by dry ice. This allowed most of the agent to condense in the sample cylinders after a test for subsequent reuse. Recycling of agent significantly reduced the total amount required to perform the series of tests.

The liquid and gas temperatures in the vessel were recorded by type E sheathed thermocouples prior to a test. Temperatures were not taken during tests because the thermal time lag through the sheath was longer than the discharge time. Attempts to measure the temperature of the fluid in the piping during discharge were unsuccessful because the unsheathed fine wire (**$13 \mu\text{m}$** diameter) thermocouple probes would break in the flow. The pressure in the storage vessel was recorded with a strain-gage-type transducer (Druck Model **330**) with a total accuracy of **0.75%** and an operating and compensated temperature range of **-54 to 150 °C**. The transducer's pressure range was 0 to **14 MPa** with a response time on the order of **1 ms**. Pressure in the piping was recorded by strain-gage type, flush-mount pressure transducers (Omega Model PX-600) with a diaphragm face diameter of **7.9 mm**. Those transducers had a nominal range of 0 to **3.4 MPa** or 0 to **6.9 MPa**, depending on the gage, stated accuracy of **1%** over the compensated temperature range of **16 to 71 °C** (the operable temperature range was **-54 to 150 °C**) with a response time on the order of **1 ms**. Transparent acrylic tube test sections with the same inner diameter as the larger diameter pipe (**15.9 mm**) were fabricated. For a limited number of tests the transparent section was connected to the piping immediately downstream from the valve reducer. A high speed movie camera operating at **500 frames per second** recorded the flow through the transparent section.

Table 1. Text Matrix

| Pipe Geometry | | | Initial Storage Vessel Conditions | | |
|---------------------|---------------|--------------------|-----------------------------------|------------------------|------------------|
| Parameter Tested | Diameter (mm) | Nominal Length (m) | Pressure (MPa) | Liquid Fill Volume (%) | Temperature (°C) |
| Constant-Head | 9.5 and 15.9 | 3.5 | 2.0, 2.5 and 3.0 | N.A. | 23 |
| Straight Pipe | 9.5 and 15.9 | 3.5 | 2.75 and 4.12 | 50 and 67 | 23 |
| Storage Temperature | 15.9 | 3.5 | 4.12 | 50 | -45 and 71 |
| 90° Bend | 9.5 and 15.9 | 3.5 and 4.5 | 4.12 | 50 | 23 |
| Tee | 15.9 | 4.5 | 4.12 | 50 | 23 |
| Expansion | 9.5 to 15.9 | 3.5 | 4.12 | 50 | 23 |
| Contraction | 15.9 to 9.5 | 3.5 | 4.12 | 50 | 23 |

The series of tests included a number of transient discharges with various initial vessel conditions. The effects of agent temperature, fill volume, and vessel pressure were investigated. Piping configurations included 3.5 m of straight pipe, straight pipe with a 90° angle bend, tee, pipe expansion and pipe contraction. Constant-head tests were performed with 3.5 m of straight piping at 3 constant vessel pressures: 3.0, 2.5, and 2.0 MPa. Table 1 details the nominal conditions for the separate tests. A total of 21 different tests were performed for each agent. A limited number of repeated tests at slightly different fill conditions were also performed.

After filling the storage vessel with agent, temperature equilibration was normally achieved in about 1 hour. Slow bubbling of the nitrogen through the liquid phase (typically 30 minutes in duration) greatly facilitated the nitrogen dissolution. For some storage vessel fills, the agent/nitrogen mixture was allowed to sit for 60 hours or longer. The pressure drop over such a long time is indicative of the level of saturation achieved by the bubbling technique. Two equilibrium calculations (using PROFISSY) were performed based on the agent mass and the pressure achieved just after bubbling and after a long time storage. Assuming the system had equilibrated after the long storage, the saturation level achieved from slow bubbling alone was approximately 90 ± 5% of the mass required for saturation. HFC-125 achieved the lowest level of saturation from the bubbling technique, while HFC-227ea and CF₃I nearly achieved complete saturation from bubbling alone. The discharge test results did not appear to be strongly influenced by differences in saturation level on the order of 10%.

Cold storage vessel tests were performed with the large diameter straight piping configuration. An insulated sheet-metal sleeve was placed around the vessel and filled with dry ice to cool the liquid contents to about -45 °C. First the vessel was filled to 1/2 liquid volume at 23 °C and pressurized with nitrogen to a total pressure of 4.12 MPa, then the dry ice was added to the cooling jacket. When the temperature of the liquid reached about -45 °C the agent was discharged.

High storage vessel temperature tests were also performed with the large diameter straight piping configuration. Electrical heating tape was wrapped around the vessel to heat up the vessel and contents. The vessel was filled to 1/2 liquid fill volume at 23 °C and pressurized with nitrogen to 4.12 MPa, then power was supplied to the heating tape. When the temperature of the liquid reached about 70 °C the agent was discharged.

RESULTS

The three selected pressures (3.0, 2.5 and 2.0 MPa) cover the bottle pressure range where most of the liquid would be discharged from the bottle for a typical transient discharge. Figure 2 is a typical constant-head pressure trace for the small diameter piping. The agent was halon 1301 with the vessel pressure fixed at 2.5 MPa, and the pipe pressure was initially atmospheric. At approximately 1000 ms the discharge valve opened. The vessel pressure dropped sharply then recovered due to the nitrogen flow from the make-up tanks. The make-up tanks solenoid valve was set to open 20 ms after the discharge valve opened (the solenoid valve requires a pressure difference to open). The make-up tanks were filled to the initial vessel pressure and quickly re-pressurized the vessel. The vessel pressure remained nearly constant until the make-up tanks valve was closed about 2.5 s after it was opened. The pipe pressure traces rose sharply after the discharge valve opened, reaching a maximum about 100 ms later and remained nearly constant until the liquid ran out of the vessel. As the liquid ran out of the vessel, the pressure started to rise in the pipe, then fall as the pipe was emptied of its two-phase fluid contents. After the make-up tank valve was closed, the bottle and pipe pressures continued to drop until the pressure equilibrated about 3.5 s after the initiation of the discharge.

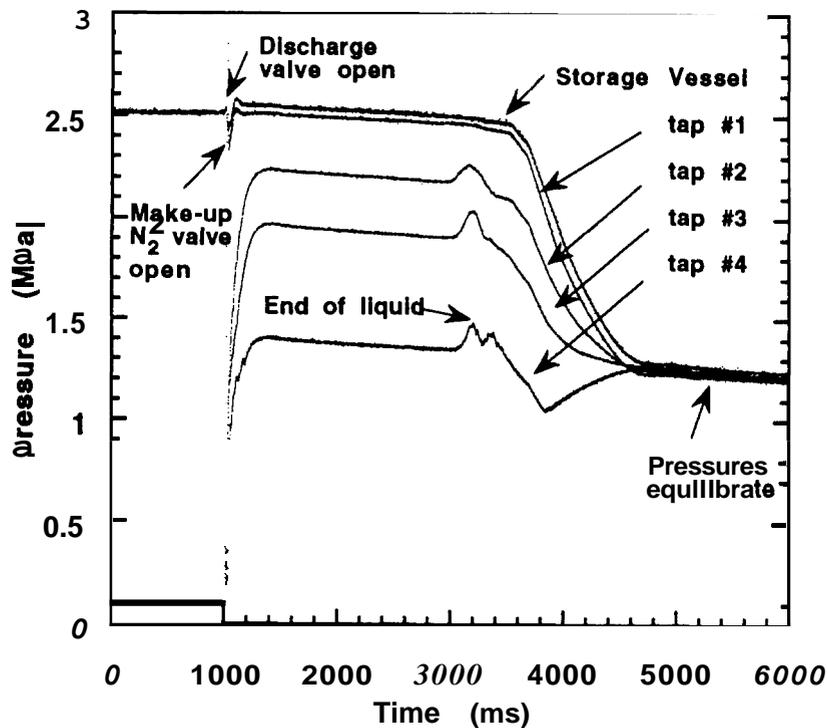


Figure 2. Pressure traces for a constant-head test. The agent was halon 1301 and the vessel pressure was maintained at 2.5 MPa. The pipe diameter was 9.5 mm and the pressure tap locations were in 1.00 m intervals starting from the valve reducer.

Experimental mass flow rates for all constant-head tests were estimated by dividing the initial liquid-phase mass (calculated by PROFISSY) by the time increment from the initial rise in the pipe pressure to the first indication that the liquid had run out of the vessel.

The transient discharge tests simulated two-phase pipe flow of realistic systems. A typical ambient temperature, straight piping test result is shown in Figure 3. Initially, the vessel was filled with HFC-125 to 1/2 liquid fill volume, pressurized to 4.12 MPa with the pipe (0.0159 m I.D.) and recovery tanks at atmospheric pressure. At approximately 1000 ms the discharge valve was opened and the vessel pressure started to drop while the pressures in the pipe and recovery tanks started to rise. The pipe pressures peaked, then started to fall with the vessel pressure. Notice that one trace, representing the second transducer, crossed over the third and fourth traces. This effect is most likely due to that transducer's incorrect response to the highly transient conditions; it was apparent in the large diameter tests, though not apparent in the small pipe diameter tests. The vessel and pipe pressures stop decreasing after about 1400 ms, achieved a local maximum, and then resumed decreasing. This pressure recovery may be due to de-gassing of nitrogen in the storage bottle. At about 1800 ms, the vessel pressure started decreasing at a faster rate, which is attributed to the discharge of the ullage contents after the two-phase mixture has left the vessel. At the same time, pipe pressures at tap locations 3 and 4 started to increase, peak, then decrease at a much faster rate which is indicative of the two-phase mixture leaving the piping followed by discharge of the ullage contents. All pressure traces equilibrate to about 1.2 MPa.

Experimental liquid discharge times were estimated for each transient discharge test as the time interval from the initial vessel pressure drop to the final hump in the last pipe pressure trace. There is some uncertainty in the liquid discharge time since the last amount of liquid draining from the vessel will not flow out as a plug, but will be entrained into the discharging ullage gas. Observations concerning individual configurations and fill conditions are not included here due to space limitations.

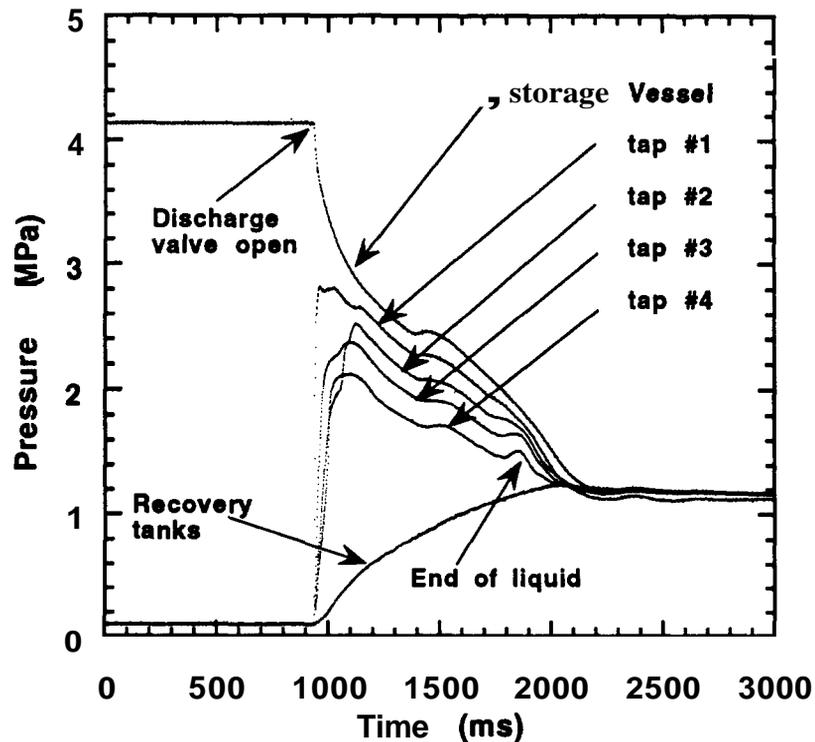


Figure 3. Pressure traces for a transient discharge test. The agent was HFC-125 filled to 1/2 liquid fill volume and pressurized to 4.12 MPa. The piping diameter was 15.9 mm and the configuration was straight piping. The pressure taps were located at 1 m intervals starting at the valve reducer.

The effects of the increasing pressure in the recovery tanks on the transient flow are identifiable, given pressure traces for the pipe and recovery tanks. If the pipe exit pressure is above the discharge pressure (recovery tanks pressure), the flow is choked and the flow rate is independent of the discharge pressure. If, however, the pipe exit pressure is equal to the discharge pressure, then the flow rate depends on the discharge pressure, and it will not achieve the maximum choked value. In some cases it appears that the recovery tanks' pressure is high enough to affect the two-phase flow from the piping during the later stage of the two-phase discharge. This observation is most evident for the following conditions: high fill volume, small diameter piping and the agents with the lower saturation vapor pressures (HFC-227ea and CF₃I). If the flow is not always choked at the pipe exit, the flow time will be slightly longer than the flow time for an atmospheric discharge. This effect probably results in not more than a 10% increase in flow time for any affected test.

The transparent test section replaced a section of tubing for a limited number of tests and high speed movies were taken during those tests. The location of the sight tube was at the exit of the vessel just after the valve reducer section. The most important observation for all of these tests was that a cloudy two-phase fluid was observed immediately after the vessel valve was opened and persisted until essentially all of the liquid contents of the vessel had emptied. This implies that bubbles nucleate somewhere before this location and two-phase flow is always present during the liquid discharge period. Earlier observations showed a clear section of fluid during flow for a period of time which was probably due to partial nitrogen saturation of the agent in the storage vessel (Cleary *et al.*, 1994).

MODEL

The experimental study yielded a lot of quantitative information on the flow characteristics of the alternative agents and halon 1301. The effects of piping configuration and initial fill condition were shown to have a significant impact on the flow characteristics. Even though a number of tests were performed, a very limited range of conditions and piping configurations were explored. Modeling the pipe flow would allow other configurations and conditions to be examined. With that in mind, a computer model was developed that predicts the steady-state and transient discharge of an alternative agent superpressurized with nitrogen from a storage bottle through piping. The modeling approach is described below. Model equations and solution technique are not included here due to space limitations, but will be included in the final report to the sponsors to be published as a *NIST Special Publication*.

The model assumes homogeneous, equilibrium two-phase compressible flow. The homogeneous assumption specifies that the gas and liquid phase are well mixed and traveling at the same velocity. This is a good assumption for bubble flow at low void fractions. Bubbles will tend to coalesce at higher void fractions; the transition from bubbly flow to plug flow occurs around a void fraction of 0.3 (Whalley, 1987). At high liquid flow rates though, large bubbles tend to be broken up. The fluid is assumed to be in thermodynamic equilibrium at all locations in the piping. Adiabatic, isenthalpic flow is assumed, greatly simplifying the analysis. The change in entropy is attributed to lost work due to frictional losses. The agent flow in the piping is always assumed to be two-phase flow for initially nitrogen-saturated bottle conditions. If the liquid agent is not saturated with nitrogen, the flowing agent is a single-phase liquid until the pipe pressure drops to the equilibrium nitrogen saturation pressure and at that point de-gassing occurs. The liquid contents in the bottle can either follow the isenthalpic pressure/density path, or be frozen as a constant density liquid until a critical pressure is reached. There is no mass transfer across the initial liquid-gas boundary in the bottle; bubbles that form in the liquid phase are assumed to stay with the liquid phase. The ullage gas expands adiabatically and isentropically, and is treated as an ideal gas. The ratio of specific heats $C_p/C_v = \gamma$ is a constant value.

The foundation for the flow prediction is formed by an application of the steady-state mechanical energy balance and continuity equation for pipe flow. *An* important assumption is that the calculation *can* proceed in a quasi-steady fashion, i.e., the upstream stagnation properties (the bottle conditions) are fixed over a time increment, and a steady mass flow rate is calculated. The small out-flow of mass changes the bottle conditions for the next time increment. Pressure drop across bends, valves, and other piping elements can be included by treating those items in terms of an effective pipe length.

The constant-head tests were simulated by fixing the upstream conditions and calculating the steady mass flow rate and the pipe pressures at the tap locations. The effective length of the 15.9 mm diameter pipe was specified as 4.13 m, 3.50 meters of pipe from the valve reducer to the recovery tanks plus 0.63 m effective length for the valve and valve reducer section (which essentially reproduces the experimental pressure drop from the bottle to the first pressure tap location). For the 9.5 mm pipe an effective length of 3.10 m was specified. There are 3.00 m of physical pipe length until the expansion to the larger pipe diameter which leads to the recovery tanks, and 0.10 m was chosen as an effective pipe length for the valve and reducer.

Figure 4 is a plot of experimentally determined flow rate versus the calculated flow rate for all of the tests. The calculated results for the small diameter tests are within 10% of the mean experimental value. For the large diameter tests, the experimental values are larger than the calculated steady values. One reason for this difference is that in the large diameter piping tests the pipe filling and emptying times are a significant fraction of the total flow time. The mass flow rate during pipe filling and emptying is higher than when the pipe is full. Given the uncertainty in the experimental values and the likelihood that the calculated steady values should underestimate the large diameter values, the results compare favorably.

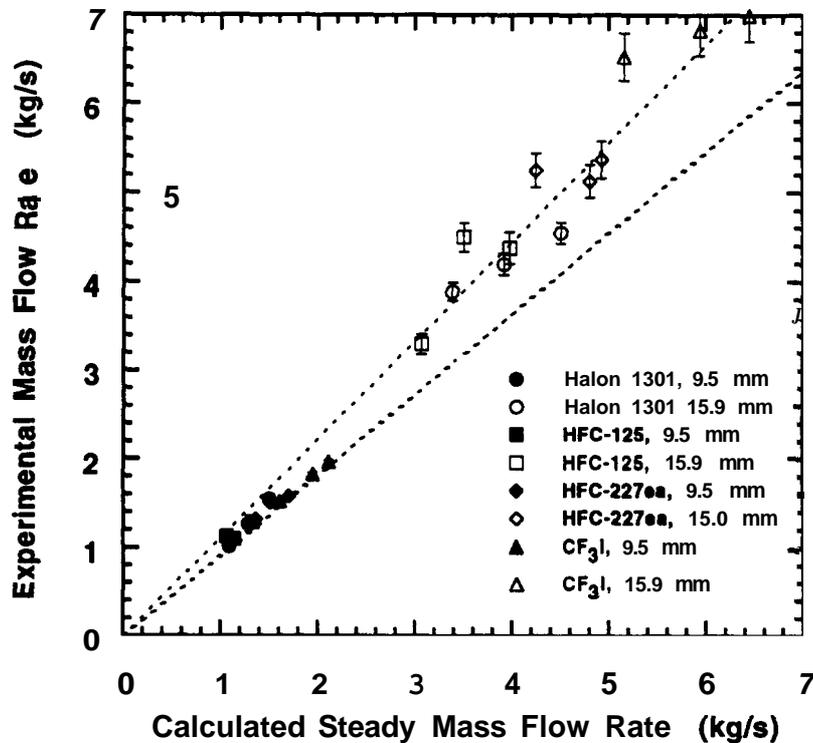


Figure 4. Experimental mass flow rate compared to calculated mass flow rate. The dashed lines represent $\pm 10\%$ deviation from the predictions. Estimated experimental measurement error is indicated by the error bars.

Calculated pipe pressures for HFC 227ea are shown in Figure 5. For all agents, the pressure predictions show good agreement with the experimental pressures and illustrate the validity of the flow assumptions. Deviations from the experimental values may be due to meta-stable flow, heat transfer, and/or departures from the assumed homogeneous flow condition.

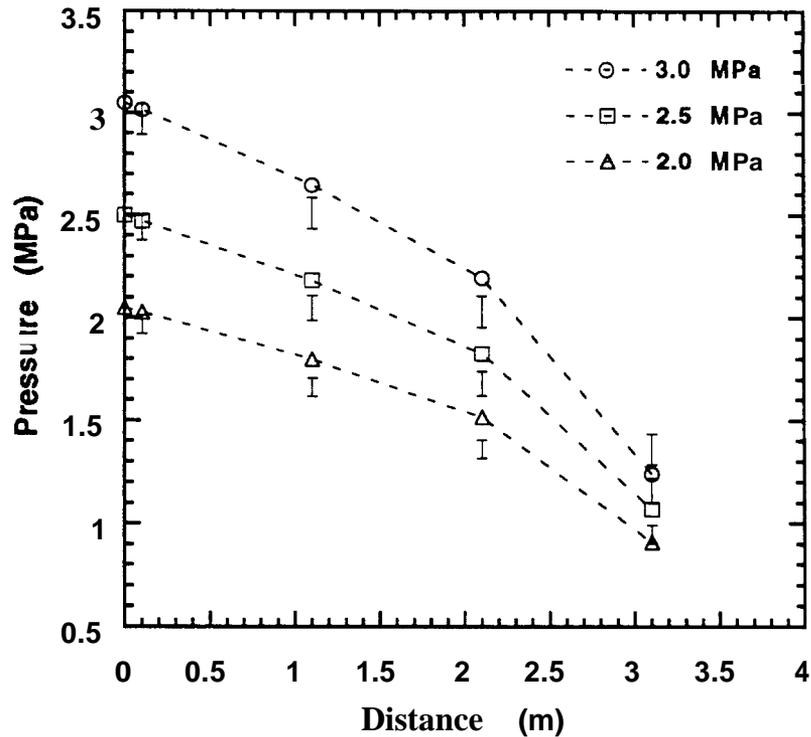


Figure 5. Pipe pressure drop as a function of distance for HFC-227ea. Calculations are presented as the symbols connected by straight dashed lines. Experimental pressures are indicated by the vertical lines with error bars. The pipe diameter was 9.5mm. The distance to the first tap location is given by an effective length of 0.10m, the following tap locations are in 1.00 m intervals.

Each transient test was simulated by the model using the experimental fill conditions. It was assumed that the mass of dissolved nitrogen was the equilibrium amount. Calculations were performed for the cases with the bottle liquid contents in thermodynamic equilibrium and repeated assuming the initially liquid contents remained as a liquid until a specified bottle de-gassing pressure was reached then bubbles formed and the contents followed the thermodynamic equilibrium path.

Figures 6a-b are the simulated pressure traces for one test (halon 1301 at 1/2 liquid fill volume and 4.12 MPa storage pressure flowing through 3.5 m of straight piping. The results from Figure 6a are for equilibrium bottle conditions, while the results for Figure 6b are for non-equilibrium bottle conditions until the critical de-gassing pressure is reached. The non-equilibrium bottle condition calculations yield vessel and pipe pressure results that compare more favorably to experiments than do the equilibrium bottle condition calculations, but requires knowledge of the de-gassing pressure for the specific conditions.

The model also describes the following flow conditions as a function of time: mean density of the fluid at the pipe exit, mass flow rate, exit velocity, exit temperature, exit quality (mass fraction in the vapor phase) and the total mass fraction discharged from the pipe.

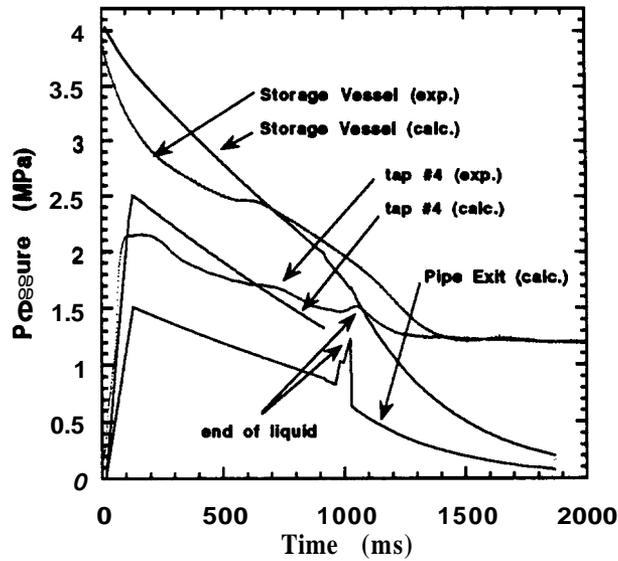


Figure 6a.

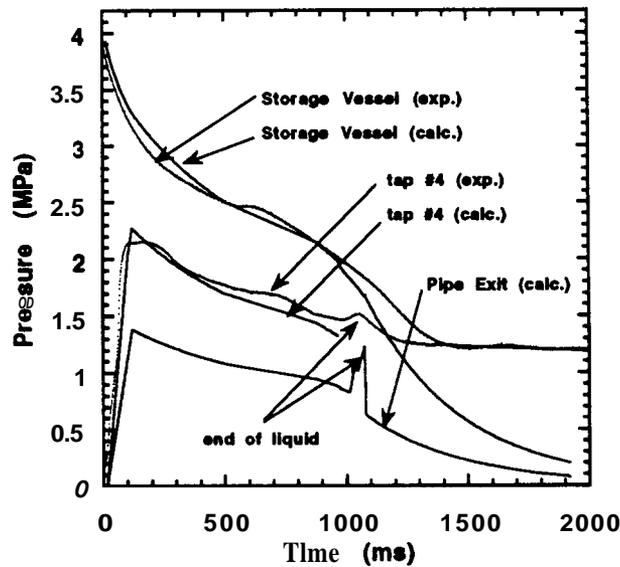


Figure 6b.

Figure 6. Simulated pressure traces for transient discharge of halon 1301. Fill conditions 1/2 liquid fill volume pressurized to 4.12 MPa and 3.5 m of 15.9 mm ID. straight piping. Experimental results for the same agent, fill condition and piping configuration are also shown. In Figure 6a the vessel contents are assumed to be in equilibrium at all times for the calculation whereas in Figure 6b the vessel contents are in the initial liquid non-equilibrium state until a de-gassing pressure (2.5 MPa, estimated from the experiments) is reached.

Figures 7a-b show the experimental liquid discharge times (discharge time of the original liquid contents) versus the calculated discharge times for all the simulated tests. The calculations based on equilibrium bottle conditions tend to be shorter than the calculations based on a fixed de-gassing pressure or no bottle de-gassing.

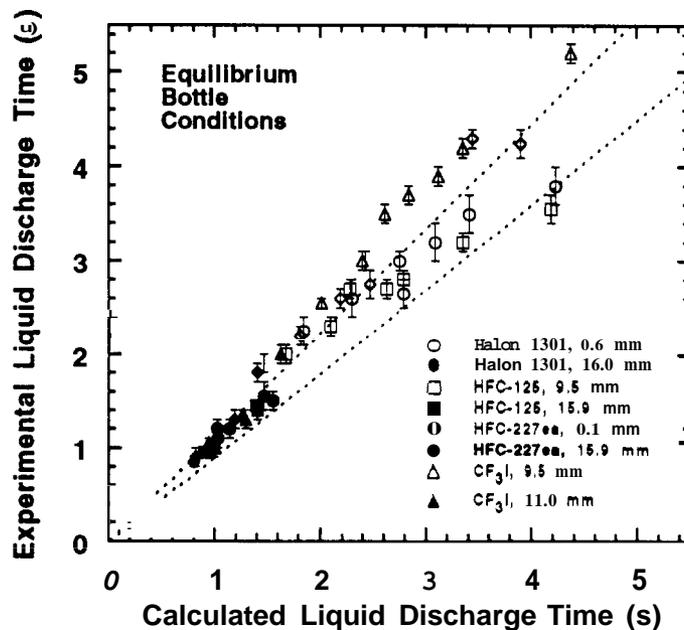


Figure 7a.

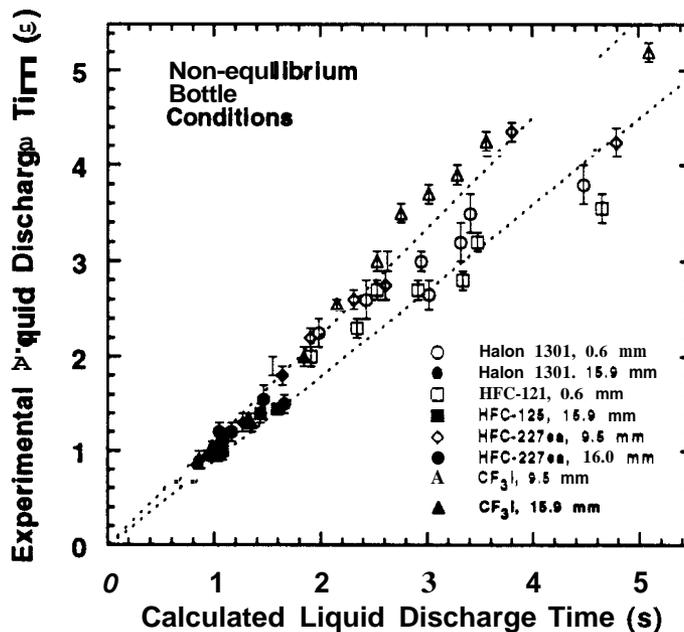


Figure 7b.

Figure 7. Experimental versus calculated liquid discharge times for transient discharge tests.

For HFC-227ea and CF₃I, there appears to be a systematic difference between experimental and predicted results for the cases with the small diameter piping. For most cases, the calculated liquid discharge time is less than **90%** of the experimental discharge time. These deviations may be due to the pressure build-up in the recovery tanks during those tests, which decreases the flow rate below the choked condition for a period of time. Another systematic trend appears to be an overprediction of the liquid discharge time for the **2/3** liquid fill condition, small piping cases. One possible explanation may be that significant heat transfer to the ullage contents may raise the pressure above the isentropic expansion condition. Since the ullage can expand by a factor of 3 before the liquid runs out, the adiabatic temperature of the ullage will be lower than the **1/2** fill case, which favors heat transfer from the vessel walls. The two-phase flow time is the longest for these tests which also favors heat transfer.

There is no obvious reason why the model cannot be extended to higher bottle pressures and larger pipe diameters. Testing at higher bottle pressure and larger pipe diameter would confirm the model's ability to predict liquid discharge times under those conditions and add confidence to extending the predictive capabilities.

CONCLUSIONS

The effects of storage bottle conditions and piping configuration on pipe flow characteristics were examined for three alternative agents and halon **1301**. All agents behaved in a similar manner to halon **1301** in nitrogen superpressurized systems. High speed movies confirmed the flows as two-phase flows. All agent flows are compressible and exhibit choking effects. Model calculations based on a simple homogeneous equilibrium description of the flow compare favorably with the experimental results.

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