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Development and Performance of an Adiabatic Expansion Nozzle for Improved Fire Extinguishers

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16. Abstract

A new fire extinguisher concept, the adiabatic expansion nozzle, extends the usefulness of fire extinguishing compounds by lowering the temperature and discharge pressure of the agent. This allows total flood type halon replacements to be used in hand-held applications and, in the instance of carbon dioxide, produces a low-pressure dry ice snow.

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EXECUTIVE SUMMARY

A device called the Adiabatic Expansion Nozzle extends the usefulness of fire-extinguishing compounds, such as carbon dioxide (CO_2) and halon alternative agents. The device employs the latent heat of vaporization of the agent to reduce the temperature and pressure of the agent emerging from the fire extinguisher. Rather than emerging from an extinguisher as a high-pressure gas, the agent is discharged as a very cold liquid or, in the case of CO_2, as a finely divided solid (dry ice). This allows firefighting agents, previously considered only for total flood applications, to behave like streaming agents, making them suitable for hand-held applications. United States Patent 6,116,049 has been granted for the device (appendix A).

PURPOSE

The purpose of this test program was to examine the feasibility of allowing a high vapor pressure gaseous firefighting agent to convert to a liquid or solid during a staged adiabatic expansion. By dropping the temperature and pressure of the extinguishing agent, the compound behaves more like a streaming (liquid) agent, such as water, rather than as a total flood agent, such as halon 1301. The two agents examined in this test program were carbon dioxide (CO_2) and trifluoromethane (HFC-23). Any candidate agent that is a gas under ambient conditions but is stored under pressure as a liquid can be used with this device, although modifications in the internal geometry may be needed to optimize performance.

INTRODUCTION

The Montreal Protocol, originally signed in 1987, called for a 50% reduction in ozone depleting substances by 1998. This was later accelerated to a complete halt in the production of halons by January 1, 1994. While aircraft have been given an exemption to allow continued use of halon extinguishers due to the potential catastrophic loss of life, substitute firefighting agents are sought to replace halons. Halon replacement agents require four characteristics: low global environmental impact, acceptable toxicity, cleanliness, and effectiveness.

Replacement agents have generally been categorized in terms of the how the agent is used. Total-flood applications are those where the agent is discharged to raise the overall concentration of agent throughout the protected space until fire suppression or extinguishment is achieved. Typical of this type of application are computer rooms or aircraft cargo compartments and engine nacelles. Streaming applications are those where the agent is discharged directly onto a fire, such as hand-held extinguishers and large firefighting apparatus. Generally, the application is determined by the vapor pressure of the candidate agent. Those agents that are at or near their boiling point at room temperature are suitable for streaming applications, while those having a low boiling temperature and high vapor pressure tend to dissipate before reaching the base of a fire. These agents are limited to total flood applications. Lowering the temperature of an extinguisher would have the effect of allowing total flood agents to be used as streaming agents, but it is not practical to store fire extinguishers in a refrigerator/freezer until usage. Achieving this would, however, mean that only a single agent would need to be purchased for both types of firefighting application.

Carbon dioxide (CO_2) is an agent that is used for both hand-held extinguishers and total flood systems. As a hand-held extinguisher, CO_2 is rated for class B fire, i.e., flammable liquids but it is not suitable for class A fires, i.e., wood or paper. Like other total flood agents, CO_2 dissipates rapidly, leaving the fire prone to reignition from smoldering embers. Also, the liquid carbon dioxide in the extinguisher is under high pressure, about 830 pound per square inch (psi) at 70°F [1]. This means, discharging the extinguisher may tend to spread a fire by blowing bits of flaming wood and paper from the localized fire site and could result in a serious problem if other flammable liquids are present.

Carbon dioxide is rather unusual as a chemical compound in that, at room pressure (760 mmHg), it exists as only a gas or solid. Most compounds make phase transitions from solid to liquid to gas as temperature increases, like ice to water to steam. Carbon dioxide, however, exists as a solid at -79ºC, but rather than melting upon warming to form a liquid, it transitions directly into the gas phase (sublimation).

EXPERIMENTAL

It has been observed that when CO_2 total flood systems discharge the protected space undergoes a rapid chilling. Upon continued CO_2 discharge into the space, the liquid changes into the two states of matter possible for this compound at room pressure; gas and solid (dry ice). In the case of hand-held CO_2 extinguishers, the high-pressure discharge is a mixture of solid, liquid, and gas, but due to the temperature of the surroundings, the CO_2 almost immediately changes to all gas. It is reasoned that, if the liquid CO_2 were converted into solid, the extinguisher would be more effective as a streaming agent. The agent would be colder and have the physical effect of lowering the vapor pressure of a liquid fuel. The exit velocity of the firefighting agent would be reduced so it would have more utility for class A (wood or paper) fires. As a solid, the agent would remain on the surface for continued suppression of the fire by sublimation to gas.

An initial test used 1/16-inch brass tubing as the flow-limiting orifice to control the rate of discharge. A 1/2-inch Swagelok® tee had the perpendicular leg adapted to the 1/16-inch brass tubing using Vespel® reducing ferrules and 1/4-inch Swagelok® fittings. One of the parallel legs was connected to a 6-inch length of 1/2-inch copper tubing capped at the other end. The 1/16-inch tubing passed through the side leg of the fitting and was bent to extend into the chamber created by the 1/2-inch copper tubing. This arrangement allowed the liquid CO_2 to pass into an expansion chamber while reversing flow direction as it passed out of the open leg of the tee. Results were not particularly encouraging. Although small pieces of dry ice spit from the device, they immediately sublimed.

Several prototypes were constructed to examine dry ice production and the effect of changing expansion volume, the length of tubing entering the expansion chamber, and allowing the expansion to occur in several stages, with additional reversals in the direction of flow. The prototypes were also tested using HFC-23, a high-pressure liquid agent that has a boiling point similar to CO_2 (-84ºC). HFC-23, however, can only form a liquid/gas mixture and will not partition into gas and solid, as does CO_2. The prototypes were made using various sizes of 1/64-in. wall brass tubing and 25-gauge (0.0218-in.) soft copper sheet soldered together.

The inlet tubing was chosen to be slightly smaller than the limiting orifice of a conventional 5-lb. CO_2 fire extinguisher. A standard extinguisher has two No. 45 drill holes (0.082 in.) perpendicular to the direction of CO_2 flow, for a flow limiting orifice of 0.01056 square inch. The new nozzle used 1/8-inch brass tubing as the inlet (inside diameter of 0.097 in. and a limiting orifice of 0.00739 square inch) to simulate the conventional CO_2 extinguisher flow rate. The brass assembly is placed inside an 8 inch length of 2-inch diameter Extren® fiberglass reinforced polyester tubing that is capped on the end the brass tubing enters. This simulates the size of the standard discharge horn on a conventional 5-lb. CO_2 fire extinguisher.

As the prototype design evolved, it was seen that multiple reversals of flow increased the dry ice yield. The amount of expansion that the liquid agent undergoes can be calculated by the change in cross-sectional area. When the flow emerges from one internal tube to another, the expansion is simply the area of the larger tube divided by the area of the smaller tube. If the smaller tube is inside the larger tube, which is capped off, the flow reverses direction. The expansion ratio is calculated by the area of the inside of the outer tube, minus the area of the outside of the inner tube, divided by the area of the inside of the inner tube. Chromel/alumel thermocouples are inserted through a small hole drilled in the end caps where flow reversal takes place. A small dab of epoxy seals the hole and holds the thermocouple in place. In this way, temperature is measured at all of the points where expansion and flow reversal takes place.

The details of construction for the final prototype for the CO_2 expansion nozzle are shown in figure 1. The nozzle, discharge horn with diagramatic representation of the flow diverter used to focus the agent, and location of temperature measurements are shown in figure 2.

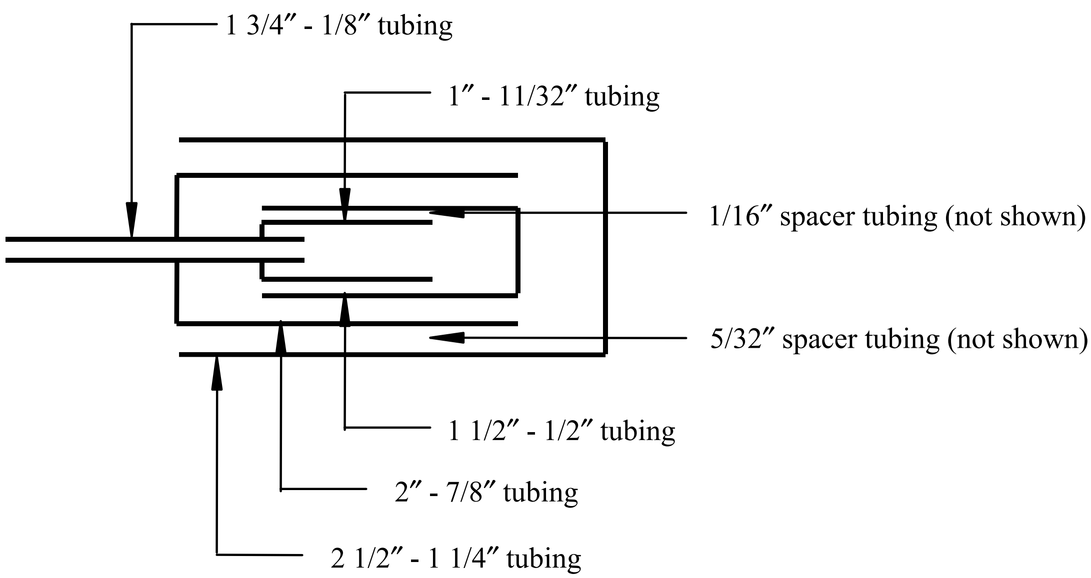

FIGURE 1. ADIABATIC EXPANSION NOZZLE

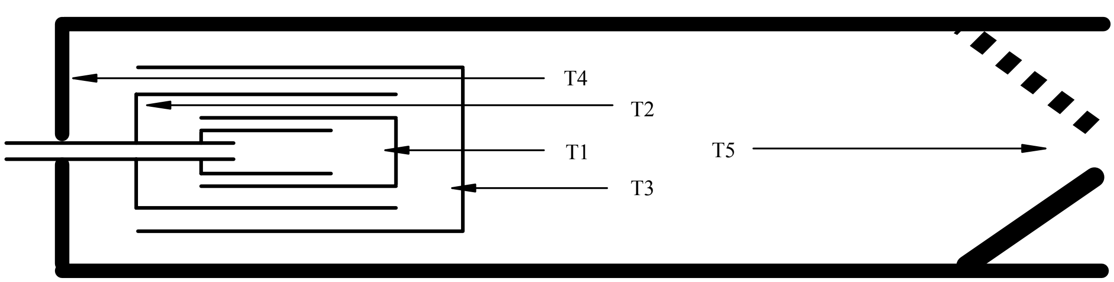

FIGURE 2. NOZZLE WITH DISCHARGE HORN

The liquid CO_2 enters the device traveling from left to right. The liquid begins to expand as it passes from the 1/8-in. tube into the 11/32-in. tube. As the gas/liquid mixture exits this tube, it reverses direction into the 1/2-in. tube. The spacers, not shown in the drawing for clarity, hold the device together. A thermocouple measures the temperature, T_1, at the end cap of the 1/2-in. tube. As the flow emerges into the 7/8-in. tube, the flow again reverses direction and temperature, $T_{2,}$ is measured at the end cap of the 7/8-in. tube. The flow again changes direction and temperature, $T_{3,}$ is measured at the end cap of the 1 1/4-in. tubing. At this point, the CO_2 exits the brass portion of the nozzle and into the discharge horn of the extinguisher where direction of flow is again reversed and temperature, T_4, is measured. At this point, the temperature is -78ºC and discharge is a gas/solid mixture. Temperature profiles of the four internal points of flow reversal are plotted along with T_5, the temperature where CO_2 exits the discharge horn, in figure 3. The cylinder valve is opened at approximately 0.83 minutes and the liquid agent is exhausted at about 0.98 minutes into the test.

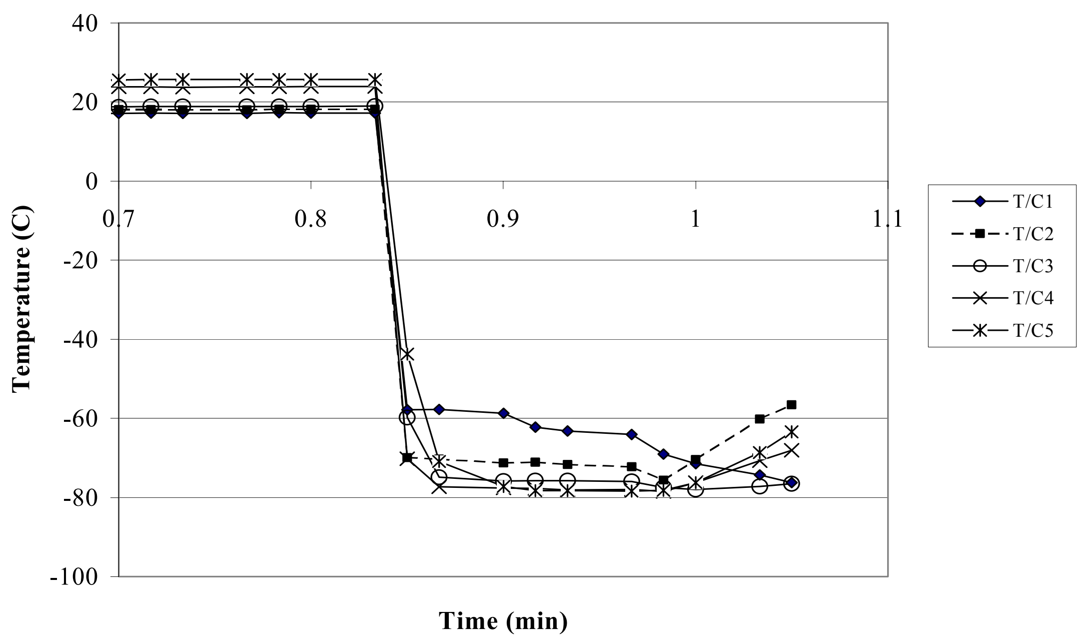

FIGURE 3. PROTOTYPE CARBON DIOXIDE NOZZLE INTERNAL TEMPERATURES

Since it is known that discharging CO_2 into enclosed spaces facilitates formation of dry ice within that space, it is difficult to determine actual yield of dry ice production. Although dry ice is visible during discharge with the CO_2 nozzle, the solid begins to sublime immediately, so actual measurement is not feasible. A simple test was designed whereby a standard document storage box had the upper flaps taped together forming on open top container 15 1/2 in. by 12 in. by 16 1/4 in. tall. The box is weighed prior to discharge of a CO_2 cylinder that is equipped with the adiabatic expansion nozzle. The nozzle is attached to the cylinder with a ball valve and is pointed directly down into the box at a height of 1 foot above the box. The CO_2 vapor pressure forced the liquid through the nozzle, much as if the cylinder were equipped with an eductor tube as on a standard CO_2 extinguisher. The cylinder is weighed before and after charging with CO_2. Immediately after discharge, the box is weighed again with the difference being the solid CO_2

caught. Comparing the amount caught and dividing by the amount placed in the cylinder gave a rough measure of the dry ice yield. This is only an approximation because dry ice deposited on the clothing of the operator and not all of the solid was caught in the box. Tests showed that between 9.2% and 11.2% of the total CO_2 discharged was caught in the box.

A prototype was also developed for HFC-23 (trifluoromethane), which consisted of a nozzle with brass tube diameters of 1/8, 9/32, 1/2, and 21/32 inches (1/64-in. wall) and a discharge horn made of 1 1/4-inch diameter Extren® (1/8-in. wall) tubing. (See figure 2 in appendix A page A-3.) In this instance there are two flow reversals where temperature measurements T_1 and T_2 are taken, with T_3 measured at the discharge horn outlet as shown in figure 4. This agent was selected because it had a vapor pressure approximately that of CO_2 at ambient temperature. Unlike CO_2, however, this liquid solidifies at a lower temperature and behaves like most substances, transitioning from solid to liquid to gas as temperature increases regardless of the pressure at which the experiment is conducted. With this agent, the only purpose is to lower the temperature and exhaust velocity from the discharge horn. It is not possible to partition from liquid to solid and gas.

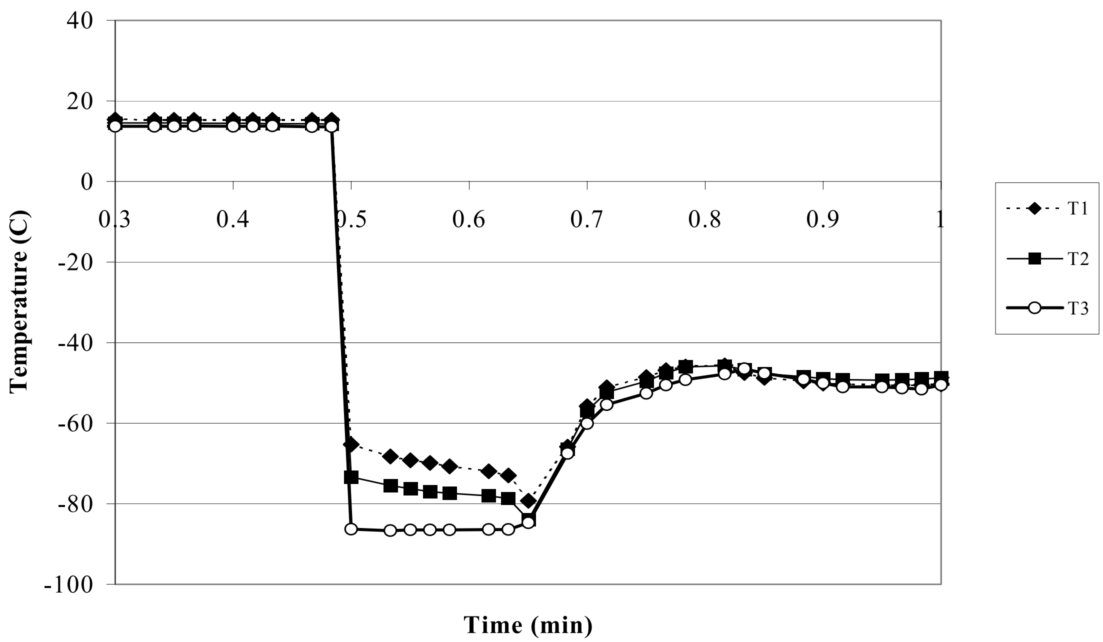

FIGURE 4. PROTOTYPE HFC-23 INTERNAL TEMPERATURES

With the HFC-23 nozzle, the discharged agent is gas/liquid stream, similar to a Halon 1211 extinguisher, and the exit velocity is greatly reduced. If HFC-23 is used with the carbon dioxide version of the nozzle, the liquid is so cold that there is virtually no exit velocity, i.e., you could pour the agent developing inside the nozzle onto the fire. Depending on the physical properties of a particular candidate agent, fewer flow reversals or smaller expansions may be desirable.

ANALYSIS

The expansion that takes place in the nozzle can be described mathematically as the change in cross-sectional area as the agent emerges from each successive internal tube. When an extinguisher is activated, liquid agent is forced up the eductor tube by the vapor pressure of the liquid. The first stage of expansion is the change of inside diameter (i.d.) of the first two tubes. Both tubes have a 0.014-in. wall thickness. The expansion factor is calculated in equations 1 to 3.

$$\left(\frac{1}{8}\right)'' \textit{tubing i.d. area} = A_1 = \pi r^2 = \pi\left(\frac{0.125}{2} - 0.014\right)^2 = \pi(0.0485)^2 = 0.007390 \; in.^2 \tag{1}$$

$$\left(\frac{11}{32}\right)'' \textit{tubing i.d.} = A_2 = \pi r^2 = \pi\left(\frac{0.3438}{2} - 0.014\right)^2 = \pi\,(0.1579)^2 = 0.07833 \; in.^2 \tag{2}$$

$$\textit{First Expansion} = \frac{A_2}{A_1} = \frac{0.07833}{0.00739} = \quad 10.60\, x \tag{3}$$

Therefore, as the liquid emerges from the 1/8-in. tube into the 11/32-in. tube, the expansion is a factor of 10.60.

The second stage of expansion has the gas/liquid mixture reversing direction of flow as the agent expands from the 11/32-in. tube into the 1/2-in. tube. The cross sectional area is the same for the second tube, 0.07833 in^2. As the agent enters the third tube, the ring-shaped area is bounded by the i.d. of the 1/2-in. tube minus the outside diameter (o.d.) of the 11/32-in. tube. The expansion factor is calculated in equations 4 to 6.

$$\left(\frac{1}{2}\right)'' \textit{tubing i.d. area} = A_3 = \pi\left(r^2\right) = \pi\left(\frac{0.500}{2} - 0.014\right)^2 = \pi(0.2360)^2 = 0.1750 \; in.^2 \tag{4}$$

$$\left(\frac{11}{32}\right)'' \textit{tubing o.d. area} = A_4 = \pi(r)^2 = \pi\left(\frac{0.3438}{2}\right)^2 = 0.09283 \; in.^2 \tag{5}$$

$$\textit{Second Expansion} = \frac{A_3 - A_4}{A_2} = \frac{0.01750 - 0.09283}{0.07833} = 1.049\, x \tag{6}$$

The second expansion is small, 1.049, the area being only 5% larger than before flow reversal.

The third stage of expansion is also accompanied with a reversal in direction of flow. The ring-shaped area between 1/2-in. tubing and 11/32-in. tubing expands into another larger ring-shaped area between 7/8-in. tubing and 1/2-in. tubing. In this instance, the 7/8-in. tubing has a wall thickness of 0.028 in. The expansion factor is 4.021 with flow reversal.

The fourth expansion occurs as the agent exits the 7/8-in. tubing and enters the 1 1/4-in. tubing while reversing direction of flow. The expansion factor is 1.569.

The fifth expansion occurs as the agent exits the nozzle and enters the discharge horn. The agent again reverses direction of flow and is moving in the initial direction of liquid flow. The discharge horn was made of Extren® fiberglass-polyester tubing which is 2 in. in diameter with a 1/8-in. wall. The expansion factor is 2.272.

The sixth and final expansion, before the agent exits the discharge horn and attains ambient pressure, is the linear expansion from the ring-shaped area between the outside of the brass nozzle and the inside of the discharge horn into the area inside of the discharge horn. The sixth expansion is 2.042.

Total expansion is determined by multiplying successive expansion stages, or

$$(10.06)*(1.049)*(4.021)*(1.569)*2.272)*(2.042) = 325.5$$

There are two linear expansions and four expansions with flow reversal.

The HFC-23 prototype allowed for a linear expansion factor of 7.11, an expansion with flow reversal of 2.25, a second flow reversal without expansion, and a last linear expansion of 7.12. The total expansion was 113.9 fold with two flow reversals.

FIRE TESTING

A standard CO_2 extinguisher has two 0.082-inch holes that control the rate at which CO_2 exits the extinguisher. The 1/8-inch tubing has an internal diameter of 0.097 inch. The standard holes have an area of 0.01056 square inch, whereas the expansion nozzle has and area of 0.00739 square inch. Thus, the flow rate of CO_2 is lower for the extinguisher equipped with the expansion nozzle, resulting in a longer discharge time.

The only existing test that must be passed by a hand-held carbon dioxide extinguisher is Underwriters Laboratories Inc.®, UL 711, "Fire Extinguishers, Rating and Fire Testing of." A 5-pound CO_2 extinguisher must pass the 5-B Flammable Liquid Fire Test of UL 711. The extinguisher must extinguish the test fire and the minimum discharge time must be 8 seconds or greater.

An extinguisher equipped with the adiabatic expansion nozzle was compared with a standard off-the-shelf Badger® fire extinguisher but against a smaller 1-B test fire. For the 1-B test, a fire pan with a surface area of 2 1/2 square feet was filled with 3 1/4 U.S. gallons of commercial grade heptane (C_7H_{16}). (A 5-B test uses a pan with a surface area of 12 1/2 square feet filled with 15 1/2 gallons of fuel.) Rather than discharge the extinguisher directly over the pan while wearing protective equipment, as is done during certification, a smaller fire was used and the attack started 10 feet from the fire. The operator moved in rapidly and discharged the extinguisher with a side to side motion, as might be done fighting an actual fire. The discharge was continued after the fire is out to determine discharge time and compare the time to fire extinguishment, as a measure of firefighting effectiveness.

The standard 5-pound carbon dioxide extinguisher had a total discharge time of 14.8 seconds and extinguished the 1-B flammable liquid fire in 5.9 seconds.

The 5-pound CO_2 extinguisher with the adiabatic expansion nozzle had a total discharge time of 17.3 seconds and extinguished the 1-B flammable liquid fire in 3.8 seconds. There was a much less vigorous discharge of the CO_2 with the adiabatic expansion nozzle. The flame front peeled away from the fuel, compared to the standard fire extinguisher, where the flame front was forced from the fuel pan. Figures 5 and 6 show the test of the adiabatic expansion nozzle attacking the fire.

Both types of CO_2 extinguisher were tried on a U.L. 711 1-A wood crib fire test. The 5-pound carbon dioxide extinguisher is not rated for class A fires, which consists of ordinary combustible materials such as wood, cloth, paper, rubber, and plastics. The 1-A fire consists of a wood crib made up of 50 pieces of trade size 2″ x 2″ spruce or fir lumber 20 inches long. They are stacked in 10 layers of 5 pieces spaced 2 inches apart and started with a preburn of 1/4 gallon of heptane.

FIGURE 5. ADIABATIC EXPANSION NOZZLE (1-B FIRE AT EXTINGUISHMENT)

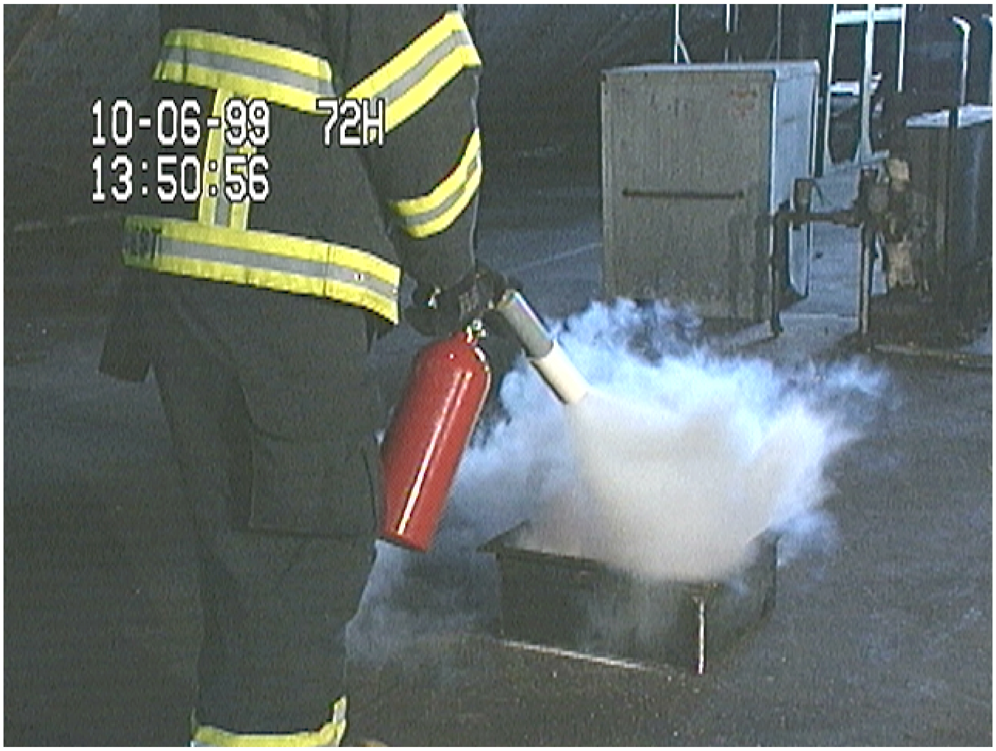

FIGURE 6. ADIABATIC EXPANSION NOZZLE (1-B FIRE AFTER EXTINGUISHMENT)

Neither type of extinguisher was successful in extinguishing a 1-A fire. The extinguisher equipped with the adiabatic expansion nozzle knocked down the fire better but was exhausted well before the crib was out. One difference between the performance of the two extinguishers was that the standard extinguisher blew embers and bits of ash approximately 15 feet from the crib itself. The adiabatic expansion nozzle fire extinguisher kept the ash basically confined to the area of the crib itself.

There are two new fire tests to evaluate the effectiveness of halon replacement agents in hand-held extinguishers that are being proposed by the Federal Aviation Administration. One is the Hidden Fire Test standard and the other is a full-scale test for extinguishing agent toxicity.

The Hidden Fire Test is basically a box containing baffles and 20 small cups of flaming heptane arranged throughout the internal volume [2]. An extinguisher is discharge through a side port of the apparatus and the number of cups that go out, compared to Halon 1211, are recorded. A stainless steel cylinder was charged with 971.4g (2.14 pounds) of HFC-23. It was equipped with a ball valve and attached to the HFC-23 version of the adiabatic expansion nozzle. The cylinder with the nozzle was inverted so that the liquid agent was forced down into the nozzle, propelled by the agent vapor pressure. When discharged, 9 of the 20 cups of heptane were extinguished, the same as with a Halon 1211 5-BC rated extinguisher. Thus, a smaller amount of HFC-23 gave performance equivalent to 2.5 pounds of Halon 1211, despite Halon 1211 having a cup burner extinguishment concentration of 3.2% compared to 12.4% for HFC-23 [3].

The second test uses three simulated aircraft seats in a test compartment the same size as a wide-body aircraft. A quart of gasoline is poured in three aliquots onto the horizontal cushion with a template assuring a set area of dispersal of the gasoline. The seat group is then lit using a spark igniter. Gas analysis is conducted for CO_2, carbon monoxide, and oxygen. The extinguisher is discharged at a distance of 6 feet from the seat assembly. The extinguisher must extinguish the fire and not produce more toxic gases than a Halon 1211 extinguisher tested in the same scenario. A test was run using the CO_2 version of the adiabatic expansion nozzle on a 5-pound carbon dioxide extinguisher. Because the extinguisher has less throw distance than a standard CO_2 extinguisher, the seat was approached at a closer distance than the specified 6 feet. The fire was successfully extinguished and there was no more carbon monoxide produced or oxygen depleted when compared to the halon extinguisher.

SUMMARY OF FINDINGS

1. A CO_2 fire extinguisher equipped with an adiabatic expansion nozzle generated low-pressure dry ice snow (solid CO_2) which demonstrated improved effectiveness for firefighting purposes. The nozzle was adapted to existing 5-B rated CO_2 extinguishers without requiring any modification other than replacing the horn. Dry ice yield exceeded 10% of the CO_2 liquid charged in the cylinder.

2. The adiabatic expansion nozzle demonstrated that halon replacement candidate agents, normally considered only for total flood applications, were delivered at sufficiently low temperature and pressure to behave like streaming agents and were suitable for hand-held applications.

3. The CO_2 nozzle was constructed the same size as the discharge horn on existing 5-B rated CO_2 fire extinguishers for direct comparability, rather than optimizing for best overall performance characteristics. No attempt was made to increase the size of the nozzle for larger extinguishers or firefighting equipment, though the concept appears to be infinitely scaleable.

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APPENDIX A—UNITED STATES PATENT 6,116,049

US006116049A

United States Patent [19]

Filipczak

[11] **Patent Number: 6,116,049**

[45] **Date of Patent: Sep. 12, 2000**

[54] **ADIABATIC EXPANSION NOZZLE**

[75] Inventor: **Robert A. Filipczak**, Linwood, N.J.

[73] Assignee: **The United States of America as represented by the Secretary of Transportation**, Washington, D.C.

[21] Appl. No.: **09/190,210**

[22] Filed: **Nov. 13, 1998**

[51] **Int. Cl.**^{7} **F25J 3/02**

[52] **U.S. Cl.** **62/603**; 62/51.2; 62/910

[58] **Field of Search** 62/910, 603, 51.2

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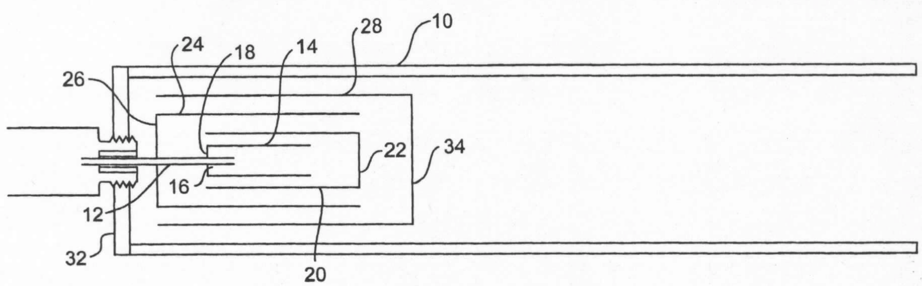
Primary Examiner—Ronald Capossela

Attorney, Agent, or Firm—Otto M. Wildensteiner

[57] **ABSTRACT**

A nozzle for producing a continuous gas/solid or gas/aerosol stream from a liquid having a high room temperature vapor pressure. The nozzle comprises a series of expansion stages, with the flow reversing direction after each expansion except the first and going over the conduit which comprised the previous expansion stage. In addition, the flow from the last expansion stage comes in contact with the inlet conduit, thereby exposing the inlet flow to the cold temperature produced in the nozzle. Since the flow in the nozzle is essentially adiabatic, the expansion in each stage takes heat from the flow in the previous stage, ultimately resulting in very low temperature flow. It is particularly useful as a fire extinguisher since it can produce solid CO_2 snow and an aerosol of HFC-23 that are "thrown" by the remaining gaseous CO_2 and HFC-23 at low exit velocities. This means that these agents can be used on Class A fires. A test nozzle using 1 liter (2.14 pounds) of HFC-23 demonstrated equivalency to a 2½ pound Halon 1211 fire extinguisher as determined by the FAA/JRC Hidden Fire Test Protocol for hand-held extinguishers.

22 Claims, 7 Drawing Sheets



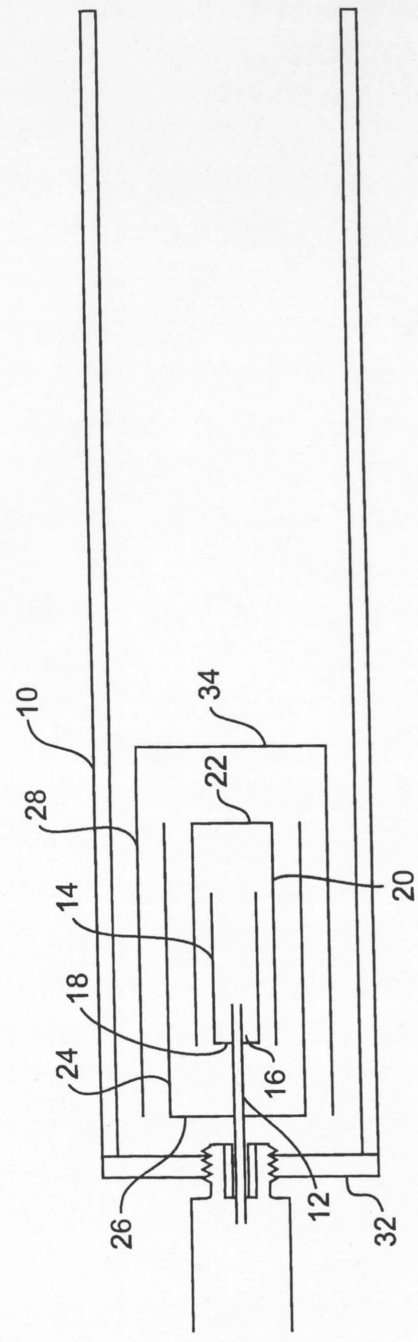


FIG. 1

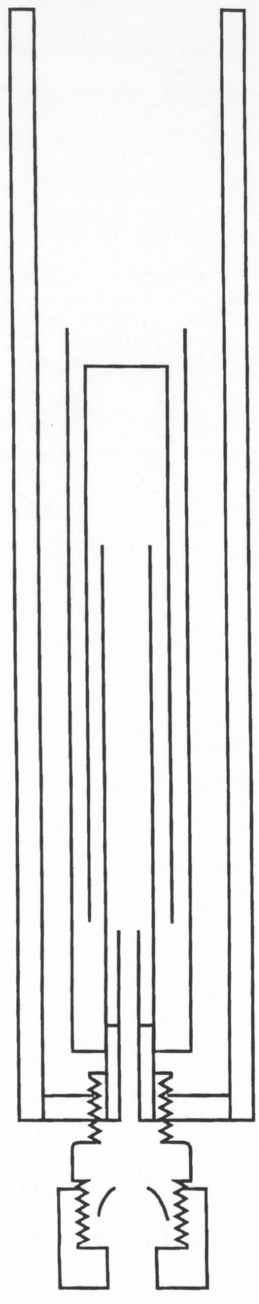


FIG. 2

ADIABATIC EXPANSION NOZZLE

STATEMENT OF GOVERNMENT INTEREST

The present invention may be made or used by or for the Government of the United States without the payment of any royalties thereon or therefor.

BACKGROUND

There are many compounds that have suitable fire-extinguishing properties but which cannot be used in fire extinguishers for use on Class A fires (i.e. paper and wood) because their exit velocities from the extinguisher nozzle are too high. These compounds have in common the fact that they have very high vapor pressures at room temperature (i.e. 500–800 psi). They are stored in a fire extinguisher as a liquid, and when directed at a fire the liquid comes out of the nozzle as a gas at a very high velocity.

Liquid carbon dioxide is one of these compounds. Carbon dioxide is well known for putting out fires, but the exit velocity from a prior art nozzle is so high that burning paper and small pieces of wood are blown about and scattered rather than being extinguished. This propagates, rather than extinguishes, the fire. Even when some of the CO_2 is converted to "snow" the exit velocity from prior art nozzles is still too high to be used on paper or wood fires.

Another compound with the same undesirable exit velocity is HFC-23. This is quite effective in putting out fires, but its high exit velocity also prevents it from being used on paper or wood fires.

A further problem with using prior art nozzles with these high vapor pressure compounds is that when they are used in a closed compartment—an aircraft cargo compartment, for example—the pressure rise in a total flood system is so sudden and so great that it can rupture the compartment because of the large volume of gas needed. Thus the cargo compartment extinguishing systems that are used on aircraft must contain Halon, which, while it is very effective and does not have the disastrous pressure rise, is damaging to the ozone layer and hence is being phased out.

Some CO_2 extinguisher nozzles produce a small amount of "snow", which is desirable since it slows down the high exit velocity and sudden pressure rise. However, these nozzles do not produce enough snow to allow their use either on Class A fires or in aircraft cargo compartments.

The prior art shows means for producing CO_2 snow or "dry ice" which is used for preserving perishables wherein the liquid CO_2 undergoes an expansion and then passes over the inlet for the liquid CO_2 (see, for example, U.S. Pat. No. 4,145,894). However, this does not convert enough liquid CO_2 to snow to reduce the exit velocity if it were used as a fire extinguisher.

OBJECTS OF THE PRESENT INVENTION

Accordingly, it is an object of the present invention to provide a nozzle for use on a fire extinguisher that can be used with high room temperature vapor pressure compounds.

It is a further object to provide such a nozzle that does not have an objectionably high exit velocity.

It is a further object to provide such a nozzle that can be used in a substantially closed compartment.

It is a further object of the present invention to provide such a nozzle that produces a mixed gas/solid output or low pressure gas/liquid output.

SUMMARY

Briefly, the present invention is a nozzle for a fire extinguisher that allows the use of fire-fighting liquids that have a high room temperature vapor pressure. It comprises a primary expansion stage and one or more secondary expansion stages for the liquid, with the flow being redirected after each secondary expansion stage so that it goes over the conduit that comprises the previous expansion stage. As it goes over the conduit it extracts heat from the flow within the conduit. Thus the flow is cooled by expansion in each stage as well as by heat transfer from stage to stage; during this process it becomes a mixed gas/liquid/solid flow. The flow from the last secondary expansion stage also comes in contact with the inlet conduit into the nozzle. After a number of stages, the flow has been cooled down to the point where a large part of it becomes a solid in the case of CO_2, and the flow exits the nozzle as a low-velocity mix of gas and solid particles. In the case of HFC-23, the liquid is chilled to the point that the flow exits the nozzle as a low pressure aerosol.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a cross section of the nozzle of the present invention for use with CO_2.

FIG. **2** shows a cross section of the nozzle of the present invention for use with HFC-23.

FIG. **3** shows a temperature profile measured within the nozzle of FIG. **1**.

FIG. **4** shows a temperature profile measured within the nozzle of FIG. **1**.

FIG. **5** shows a temperature profile measured within the nozzle of FIG. **2**.

FIG. **6** shows a temperature profile measured within the nozzle of FIG. **2**.

FIG. **7** shows a flow concentrator at the exit of the nozzle which directs flow toward the axis of the nozzle.

DESCRIPTION OF THE PREFERRED EMBODIMENT

As shown in FIG. **1**, a nozzle for use with CO_2 according to the present invention comprises an outer housing **10** surrounding a series of expansion stages for the CO_2. Outer housing **10** also comprises the conduit for the final expansion of the liquid. The liquid enters the nozzle through conduit **12**, then as it exits conduit **12** into primary expansion conduit **14** it expands since the cross-sectional area of conduit **14** is larger than the cross-sectional area of conduit **12**. As can be seen there is a volume **16** approximately ¼ inch deep behind the exit from conduit **12** formed by end wall **18** on conduit **14**; this volume aids in the expansion of the liquid and produces a larger yield of desired products. The flow then expands into secondary expansion stage conduit **20**, where it cools further. Conduit **20** is closed at its end by end wall **22**, which causes the flow to reverse direction and pass back over conduit **14**. As the flow passes back over conduit **14** it extracts heat from the flow in conduit **14**.

The flow exits from conduit **20** into another secondary expansion stage, conduit **24**, where it expands again and cools further and is caused to reverse direction again by end wall **26** on conduit **24**. It then passes over conduit **20**, where it extracts heat from the flow in conduit **20**.

The flow goes through another expansion into conduit **28** and reversal where it cools and reverses direction, again passing over the conduit which forms the previous expansion stage and extracting heat from that stage. During each expansion more of the liquid is converted to a gas or a solid, with the flow being a mixture of varying proportions of liquid, gas, and solid. This mixture passes over the conduit which forms the previous stage and extracts heat from that stage. After the final expansion out of conduit **28**, however, it also comes in contact with conduit **12** which forms the inlet to the nozzle, thereby exposing the inlet flow to the temperature created by the last of the expansions.

Additionally, it was found that the addition of means to focus the flow toward the centerline of the exit nozzle increased the size of the dry ice particles when using CO_2. This was done by adding vanes **30** to the inside of outer housing **10** as shown in FIG. **7**. Vanes **30** are mounted to the inside of outer housing **10** at an angle to its centerline and direct the flow toward its centerline, thereby focusing the outlet flow. This causes additional turbulence in the flow which takes work out of the flow, thereby lowering its temperature to–82 degrees C. which is below the temperature of solid CO_2 at room pressure (i.e.–76 C).

The flow reversals inside the nozzles also cause turbulence in the flow, taking work out of the flow and contributing to the lowering of the temperature of the flow.

Since it is desirable that heat be transferred from one stage to the next, the conduits within the nozzle are preferably made of a material having good thermal conductivity such as brass. The outer housing, however, should be made of a material having a low thermal conductivity since it is desirable that the flow remain as cold as possible as long as it is within the nozzle.

Thus the liquid, rather than entering the series of expansions at room temperature, enters the series of expansions at a very low temperature. After it goes through an expansion, each of which except the first passes over the conduit from which it most recently exited, it extracts heat from the flow in the conduit from which it most recently exited. Since the inlet flow is exposed to the temperature of the flow after the final expansion into outer housing **10**, there is very little heat to be extracted from the incoming liquid by the expansions. The result is a very rapid and efficient conversion of the liquid CO_2 to solid particles or snow, as evidenced by the steep temperature drops in FIGS. **3** and **4**.

The nozzle for use with CO_2 shown in FIG. **1** had an overall expansion ratio of approximately 325, broken down as follows: the first expansion ratio into conduit **14** was 10.60; the second expansion ratio into conduit **20** (the first with flow reversal) was 1.05; the third expansion ratio into conduit **24** (and second flow reversal) was 4.02; the fourth expansion ratio into conduit **28** (and third flow reversal) was 1.57; the fifth expansion ratio into the rear of outer housing **10** (and final flow reversal) was 2.27; and the sixth expansion ratio as the flow cleared the internal conduits was 2.04. The overall length of the nozzle (i.e. outer housing **10**) was chosen to be 8 inches, the same as a conventional CO_2 fire extinguisher nozzle, in order to eliminate any effects due to a different nozzle length.

In this nozzle conduit **12** was ⅛ inch brass tubing that projected approximately ¼ inch beyond end wall **18**; conduit **14** was 11/32 inch brass tubing one inch long; conduit **20** was ½ inch brass tubing 1½ inches long; conduit **24** was ⅞ inch brass tubing 2 inches long; conduit **28** was 1¼ inch brass tubing 2½ inches long; and outer housing **10** was 2 inch O.D. phenolic tubing 8 inches long with ⅛ inch wall thickness. All internal tubing was 1/64 inch wall tubing. End wall **26** was approximately ¼ inch from end wall **32**; end wall **34** was approximately ½ inch from end wall **22**; and end wall **18** was approximately ½ inch from end wall **26**. All end walls were of minimum thickness brass sheet. The concentric conduits were held in place by short sections of minimum wall thickness brass tubing (not shown) of the proper diameter that were epoxied in place. The overall expansion ratio of the nozzle was approximately 325.

FIG. **2** shows a nozzle according to the present invention for use with HFC-23 (trifluoromethane). It utilizes the same principles, but has two fewer expansion stages (i.e. 4 expansions instead of 6). It was found that 6 expansions of HFC-23 reduced the effectiveness of the nozzle as a fire extinguishing nozzle, hence this nozzle has only 4 expansion stages and 2 flow reversals. In fact, with 6 expansions HFC-23 came out of the nozzle as a liquid at practically zero velocity; reducing the number of expansions to 4 caused it to exit as a low pressure aerosol, which made it a desirable fire-fighting nozzle. The fact that the internal conduits are longer in this nozzle than in the CO_2 nozzle results from the fact that this nozzle was the first one developed, before an attempt was made to optimize the length of the internal conduits as was done with the CO_2 nozzle of FIG. **1**. The length of the outer conduit is arbitrary; it does not match the length of an existing HFC nozzle as was done with the CO_2 nozzle.

FIGS. **3** and **4** show representative temperature profiles for the nozzle of FIG. **1** (i.e. CO_2 as the fire-fighting fluid). T_1, T_2, T_3, and T_4 are the temperatures measured at the points of the first, second, third, and fourth flow reversals, respectively. As can be seen, T_4, the temperature at the last reversal, is the lowest of the temperatures and remains fairly constant at somewhat below –80 degrees C. in FIG. **4** and somewhat below –90 degrees C. in FIG. **3**. The fluctuations in the other temperatures are not understood at this time. The variations between the profiles of FIGS. **3** and **4** are thought to be experimental error.

FIGS. **5** and **6** show representative temperature profiles for the nozzle of FIG. **2** (i.e. HFC-23 as the fire-fighting fluid). T_1 and T_2 are the temperatures measured at the points of the first and second flow reversals, respectively. T_3 is the temperature measured at the exit of the last expansion into the outer housing; it is the lowest and remains fairly consistant at approximately –90 degrees C. The reason that these temperature profiles do not exhibit the variations of the corresponding temperature profiles in the nozzle of FIGS. **3** and **4** is not known at this time.

In FIGS. **3–6** the initial constant temperature portions of the curves are due to the time interval between turning on the instrumentation and opening the valve to start the flow of fluid, which was done to establish baseline conditions. Once the fluid began to flow the temperature dropped almost instantly. Likewise, the increase in temperatures at the end of the run in FIGS. **5** and **6** is due to the interval between exhaustion of the fluid and turning off of the instrumentation. There were no vanes in the nozzles used in these figures; the temperature of CO_2 snow produced by a nozzle with vanes was determined by using such a nozzle to produce a pile of CO_2 snow on the ground and measuring its temperature with a thermocouple.

Initially it was thought that the internal conduits should be made fairly long, in order to promote maximum heat exchange. However, subsequent testing showed that shorter conduits were better; therefore it is thought that the conduits should be made as short as practicable from a manufacturing standpoint. No attempt was made to optimize the length of outer housing **10** or the expansion ratios between stages.

Because of the efficient conversion of liquid CO_2 to solid, the exit velocity is low. This allows a CO_2 extinguisher having a nozzle of the present invention to be used on a Class A fire since the low exit velocity will not scatter burning pieces of paper or wood. Two standard 5 pound CO_2 extinguishers, one with a prior art nozzle and one equipped with a nozzle of the present invention, were tested on a standard Underwriter's Lab Class 1A fire (wood crib, 50 pieces of 2 by 2 wood ignited with 1 liter of heptane, 8 minutes preburn). The extinguisher with the prior art nozzle was completely unsuccessful; it fanned the fire, scattering ash approximately 6 feet, with no reduction in the size or intensity of the fire. The extinguisher having a nozzle of the present invention did not scatter the fire and reduced the size of the fire. Some deposition of CO_2 snow on the top members of the crib was seen, although the extinguisher was emptied before the fire was completely put out.

While shown herein as having four secondary expansion stages for CO_2 and three for HFC-23, the present invention contemplates the use of as many secondary expansion stages as are necessary to achieve the degree of cooling desired. Thus in practice, depending on the liquid used and the outlet flow conditions desired, there may be more or fewer than the number of secondary expansion stages shown herein.

Likewise, while shown herein as being used with CO_2 and HFC-23, the nozzle of the present invention can be used with any liquid having a very high vapor pressure at room temperature, and for purposes other than fire fighting.

The nozzle of the present invention can also be used to produce solid blocks of the liquid for whatever purpose desired. That is, rather than directing the CO_2 snow produced by the nozzle at a fire, the snow could be directed into a collecting chamber and then formed into blocks of dry ice as is well known in the art.

I claim:

1. A nozzle for converting a liquid having a high room temperature vapor pressure to a continuous mixed gas/solid or gas/liquid stream which comprises an inlet conduit for said liquid, said inlet conduit directing said liquid into a primary expansion stage where said liquid undergoes a first expansion, and one or more secondary expansion stages, each of said secondary expansion stages comprising a conduit which causes said expanded liquid to reverse direction and flow over the outside of the conduit from which it most recently exited, and an outer housing for said nozzle surrounding said expansion stages.

2. A nozzle as in claim **1** wherein said conduits are concentric.

3. A nozzle as in claim **2** wherein said expanded liquid from the final expansion stage contacts said inlet conduit.

4. A nozzle as in claim **3** further including means in said outer housing to focus said expanded liquid toward the centerline of said nozzle.

5. A nozzle as in claim **4** wherein said means to focus comprises vanes attached to the inside of said nozzle outer housing.

6. A nozzle as in claim **2** wherein said conduits are made of a material having a high thermal conductivity.

7. A nozzle as in claim **6** wherein the outer housing for said nozzle is made of a material having a low thermal conductivity.

8. A nozzle as in claim **6** wherein said material is brass.

9. A nozzle as in claim **2** wherein said liquid is HFC-23.

10. A nozzle as in claim **2** wherein said liquid is liquid CO_2.

11. A nozzle as in claim **2** wherein said vapor pressure is 500–800 psi.

12. The method of creating a continuous mixed gas/solid or gas/liquid stream from a liquid having a high room temperature vapor pressure which comprises introducing said liquid into a first conduit, causing said liquid to undergo a first expansion while flowing in a first direction, causing said expanded liquid to reverse direction one or more times and undergo another expansion in another conduit each time it reverses direction, and after each reversal of flow direction causing said expanded liquid to flow over the outside of the conduit from which it most recently exited.

13. The method of claim **12** further including aligning said conduits concentrically with one another.

14. The method of claim **13** further including contacting said first conduit with the expanded liquid from the last of said expansions.

15. The method of claim **14** further including focusing said expanded liquid toward the centerline of the last of said expansion conduits.

16. The method of claim **14** further including constructing all but the last of said conduits of a material having a high thermal conductivity.

17. The method of claim **16** further including constructing the last of said conduits of a material having a low thermal conductivity.

18. The method of creating a continuous mixed gas/solid or gas/liquid stream from a liquid having a high room temperature vapor pressure which comprises flowing said liquid in a first conduit and causing said liquid to undergo an expansion by flowing into a larger conduit, causing said expanded liquid to reverse its direction of flow one or more times and each time undergo another expansion into a larger conduit prior to said flow reversal, and after each expansion causing said expanded liquid to flow over the outside of the conduit from which it most recently exited.

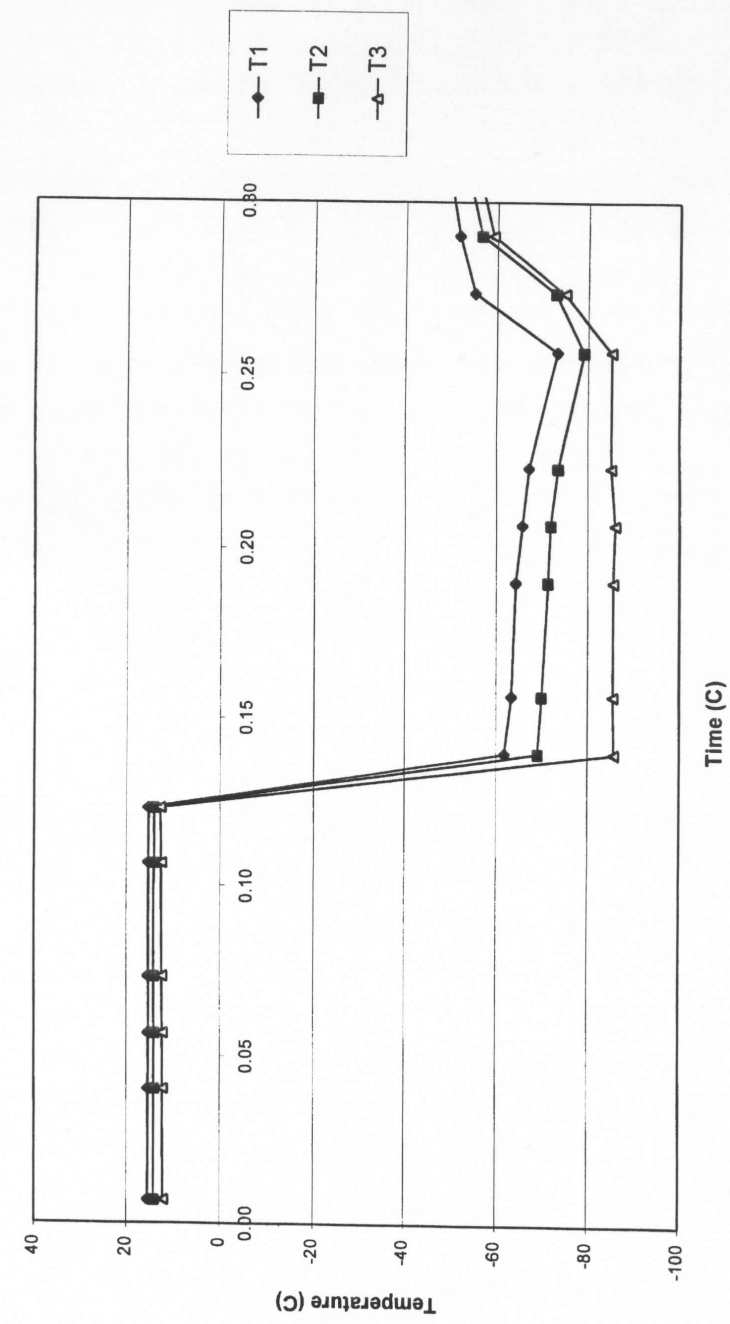
19. The method of claim **18** further including aligning said conduits concentrically with one another.

20. The method of claim **19** further including contacting said first conduit with the expanded liquid from the last of said series of expansions.

21. The method of claim **20** further including constructing all but the last of said conduits of a material having a high thermal conductivity.

22. The method of claim **21** further including constructing the last of said conduits of a material having a low thermal conductivity.

* * * * *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T3
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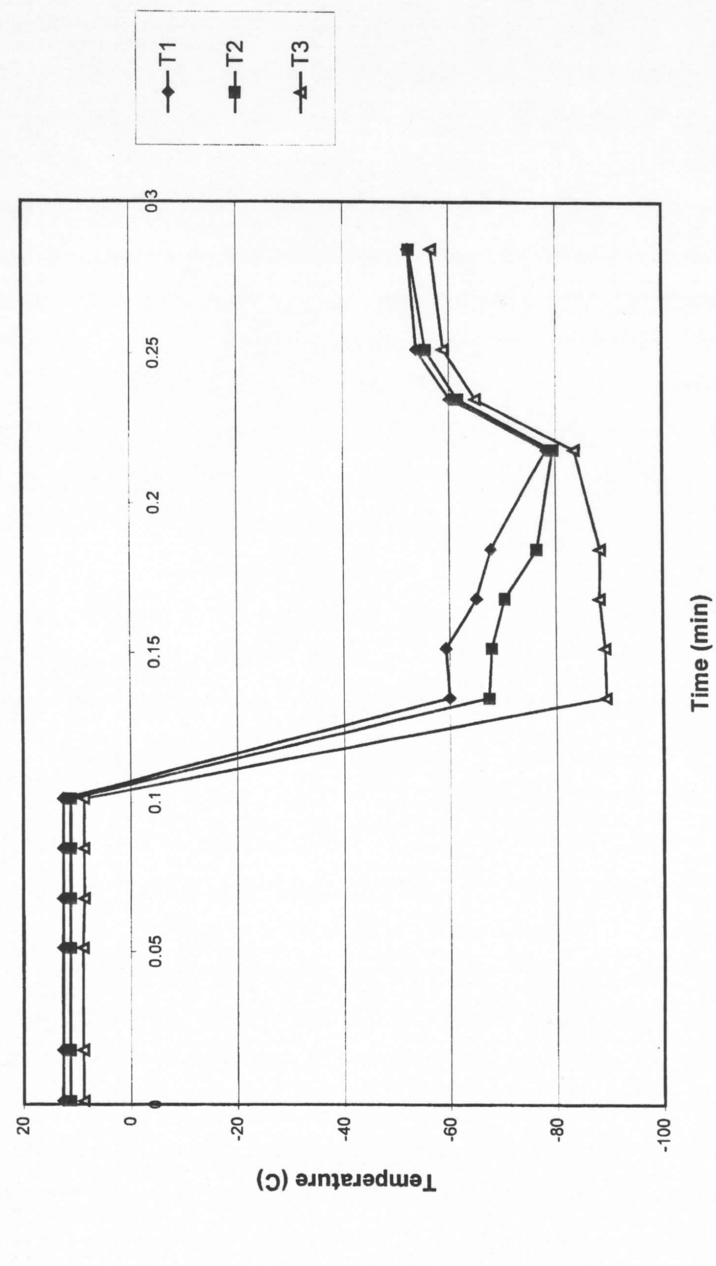
Figure 5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-100

Figure 6

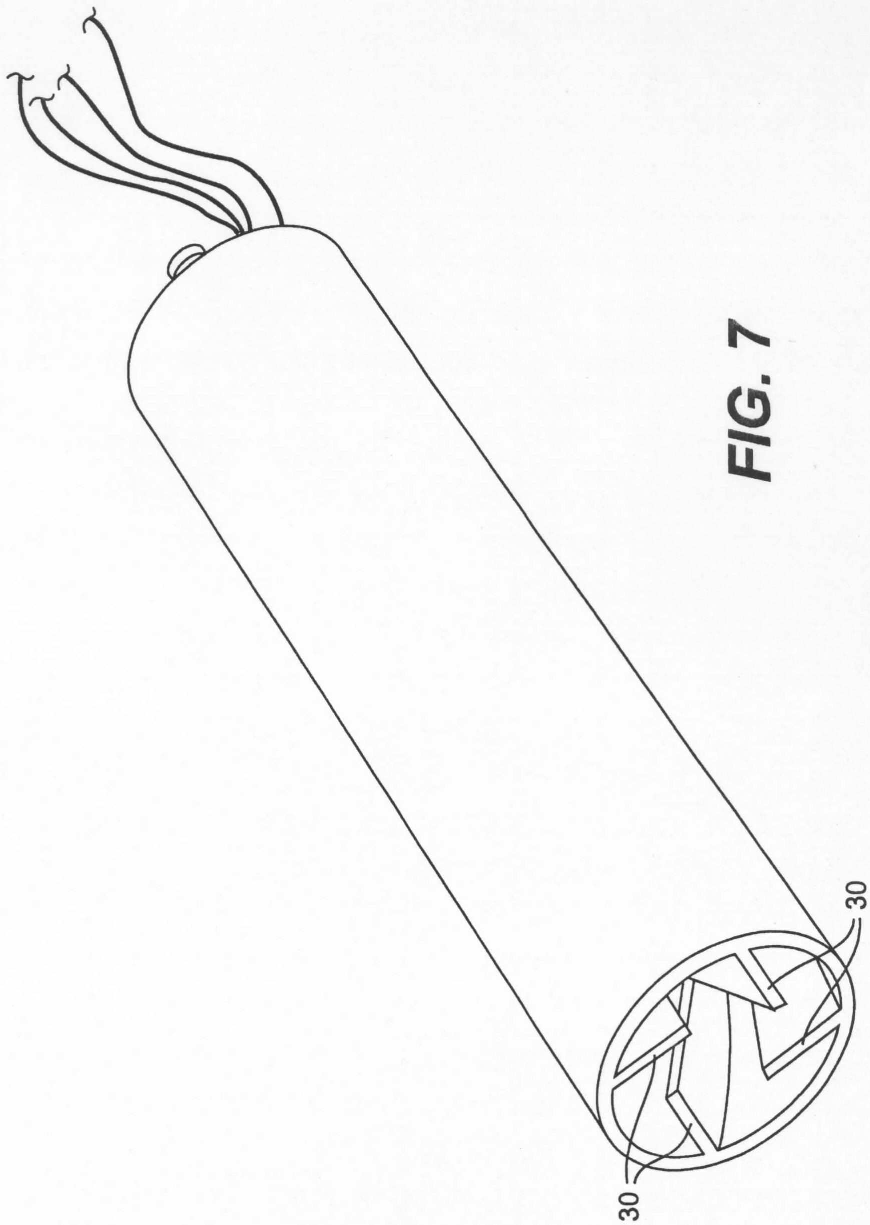

FIG. 7

APPENDIX B—ADIABATIC EXPANSION NOZZLE THERMODYNAMIC ANALYSIS

For a gas at temperature, pressure and volume, T_1, P_1, and V_1, that undergoes a quasi-static adiabatic expansion to T_2, P_2, and V_2, the pressures are related to volumes as [B-1]:

$$dQ = C_v\,dT + P\,dV \tag{B-1}$$

$$dQ = C_p\,dT - V\,dP \tag{B-2}$$

Since the process is adiabatic, dQ = 0 so,:

$$V\,dP = C_p\,dT \tag{B-3}$$

$$P\,dV = -\,C_v\,dT \tag{B-4}$$

Dividing the equation B-3 by equation B-4,

$$\frac{dP}{P} = -\frac{C_p}{C_v}\frac{dV}{V} \tag{B-5}$$

Denoting the ratio of heat capacities as $\gamma = \dfrac{C_p}{C_v}$,

$$\frac{dP}{P} = -\gamma\frac{dV}{V} \tag{B-6}$$

$$\int_{P_1}^{P_2}\frac{dP'}{P'} = -\gamma\int_{V_1}^{V_2}\frac{dV'}{V'} \tag{B-7}$$

$$\ln\left(\frac{P_2}{P_1}\right) = -\gamma\ln\left(\frac{V_2}{V_1}\right) \tag{B-8}$$

$$\ln\left(\frac{P_2}{P_1}\right) = \gamma\ln\left(\frac{V_1}{V_2}\right) \tag{B-9}$$

$$\ln\left(\frac{P_2}{P_1}\right) = \ln\left(\frac{V_1}{V_2}\right)^{\gamma} \tag{B-10}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} \tag{B-11}$$

Since the initial state is $P_1 = \frac{nRT_1}{V_1}$, and the final state is $P_2 = \frac{nRT_2}{V_2}$,

$$\left(\frac{\frac{nRT_2}{V_2}}{\frac{nRT_1}{V_1}} \right) = \left(\frac{V_1}{V_2} \right)^{\gamma} \quad \text{(B-12)}$$

$$\left(\frac{\frac{T_2}{V_2}}{\frac{T_1}{V_1}} \right) = \left(\frac{V_1}{V_2} \right)^{\gamma} \quad \text{(B-13)}$$

$$\left(\frac{T_2}{T_1} \right) = \left(\frac{V_1}{V_2} \right)^{\gamma} \left(\frac{V_2}{V_1} \right) \quad \text{(B-14)}$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{\gamma-1} \text{ or } \frac{T_2}{T_1} = \left(\frac{V_2}{V_1} \right)^{1-\gamma} \quad \text{(B-15)}$$

For CO_2, $\gamma = \frac{C_p}{C_v} = 1.310$ [B-2], so

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{1-1.310} \quad \text{(B-16)}$$

For the CO_2 nozzle, the expansion volume $\frac{V_1}{V_2} = 325.5$, $\frac{T_2}{T_1} = (325.5)^{-0.310} = 0.166$, from which $T_2 = 49.5°K$, where $T_1 = 298°K$.

The nozzle efficiency of conversion of CO_2 to its solid form is calculated as follows. The total enthalpy associated with the quasi-static reversible expansion would be $\Delta H = C_p \Delta T$. The heat capacity associated with a drop in temperature from 25°C (298°K) to 50°K is 37.71 Joules/mole [B-3] or 9.35 KJ/mole. Of that amount, the enthalpy change to drop the temperature of the gas to its freezing point, -79°C (194°K) is the heat capacity of 36.37 Joules/mole time the temperature change of 104°C, or 3.78 KJ/mole. The remaining 5.57 KJ/mole is used to convert the CO_2 to its solid form, dry ice. The heat of fusion for CO_2 is 7.95 KJ/mole [B-4] and the heat of vaporization at 25°C is 10.66 KJ/mole [B-5], so the theoretical efficiency is 5.57/(10.66+7.95) or 30% conversion. This exceeds the measured fraction because of inefficiencies of the collection method and because the nozzle process is neither adiabatic nor reversible. In that there are 5 incremental expansions, the P-V work approaches the maximum value that would be achieved in an infinite number of expansion steps. The reversal of flow allows for incremental depressurization and provides an impact and residence time mechanism for agglomeration of CO_2 into a stream of macroscopic particles that sublime at a lower rate due to lower surface to volume ratio.

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