NISTIR 6733

Transient Application, Recirculating Pool Fire, Agent Effectiveness Screen: Final Report, NGP Project 3A/2/890

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EXECUTIVE SUMMARY*

Because of its many positive attributes, halon 1301, or trifluorobromomethane (CF_3Br), has been used as a fire extinguishing agent in many applications including aircraft, ships, and specialized structures. Due to its high ozone depletion potential, however, world-wide production was halted in 1994. In the search for a long-range replacement, novel types of extinguishing agents and delivery mechanisms are under development. To gauge the suitability of a replacement agent, methods are needed to evaluate the material's suppression effectiveness under conditions that relate to field applications.

In this study, a laboratory-scale facility has been developed to screen the suppression effectiveness of agents that are delivered in a transient fashion such as solid propellant gas generators. The transient application, recirculating pool fire (TARPF) agent effectiveness screen features a propane fire stabilized behind an obstruction, which is known to be a highly challenging suppression configuration. The character of the flame and the impact of the air flow, fuel flow, obstruction geometry, and rate of agent addition on the amount of material needed for suppression are evaluated for N_2, CF_3Br, and a solid propellant gas generator (SPGG). The importance of the injection process on the flow field and the transport of the agent downstream is examined, and a simple mixing model is used to explain the observed trend of decreasing suppressant mole fraction with increasing injection duration, even for agents as different as CF_3Br and N_2. Direct numerical simulation of the suppression event is shown to successfully predict the quantity and rate of N_2 required to extinguish the flame based upon a published global reaction rate for premixed propane/air flame propagation.

Important Findings:

- The minimum mole fraction of agent for suppression, normalized by the cup burner value, correlates with $[1 - \exp(-\Delta t/\tau)]^{-1}$, where Δt is the injection time interval and τ characterizes the mixing time behind the obstacle in the flow.
- The general character of the flame and its extinction by a thermal gaseous agent is captured by a direct numerical simulation of the flow based upon single-step chemistry, and numerical experiments have corroborated the simple correlation of the experimental data for N_2.
- The measured difference between the decrease in agent storage bottle pressure and the arrival of the agent at the fire highlight the importance of determining the agent concentration locally and the difficulty in relating changes in bottle pressure to actual mixing conditions.
- For the first time, both compressed and solid-propellant generated gases can be compared side by side, and the effect on performance of different formulations, particle loadings and burning rates for various SPGG designs can be unambiguously discriminated.
- When the temperature of a hot surface downstream of the pool is above 800 ^oC, the flame, following suppression, will reignite and stabilize on the hot surface. At a temperature below 800 ^oC, the number of reignitions approaches zero. This result is in contrast to when the hot surface is located between the stabilizing step and the fuel pool, in which a delayed reignition can be observed at temperatures as low as 400 ^oC.
- The effectiveness of suppression with a liquid agent is dependent upon how well the droplets are entrained into the flame zone downstream of the stabilizing obstacle.

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*The content of this report is the same as that found in NISTIR 6733 (see bibliography).

ACKNOWLEDGEMENTS

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DISCLAIMER

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INTRODUCTION

The Fire Suppression Problem

Water sprinklers are commonly chosen to automatically protect buildings and their contents against fire because sprinklers are highly reliable, inexpensive to install and maintain, and water is non-toxic and friendly to the environment. Alternatives to water suppression are usually required if the situation calls for a very rapid response, if the primary fuel source is a gas or an evaporating liquid, if the protected space contains electrically energized or other water sensitive equipment, or if the application is weight and volume limited. Until recently, one would most likely find halon 1301, or trifluorobromomethane (CF_3Br), as the fire extinguishing agent alternative to water, especially if people had a chance of being exposed at the time of discharge. Due to its high ozone depletion potential, however, world-wide production of CF_3Br was halted in 1994.

In spite of almost a decade of significant research activity, no single chemical or suppression system has been identified that has all the positive attributes of halon 1301. Depending upon the application, one or another candidate system may appear to hold promise. Full-scale suppression testing is always essential to demonstrate acceptability, in spite of the fact that the full-scale tests are strongly influenced by the initial and boundary conditions surrounding the fire and suppression event. Complex, non-linear relationships among the agent, the flow field, and the fire cannot be unraveled from these full-scale suppression tests because critical parameters cannot be controlled tightly enough and the number of tests is constrained by cost, time, safety and environmental considerations.

The U.S. Department of Defense is committed to reducing its dependence on halon 1301 and has made great strides in this direction by eliminating non-essential uses, totally revamping its fire suppression system certification and recycling procedures, and replacing halon systems with alternative technologies where possible. There remain some applications where no substitute chemical or system has been judged satisfactory, and several others where the alternatives identified to date are saddled with serious deficiencies. One of these applications is for military aircraft, which are particularly vulnerable to fire during combat and also need in-flight fire protection during routine missions, a need shared by the commercial fleet.

The amount of a gaseous agent required to extinguish fires in full-scale engine nacelles varies greatly with the geometry of the test fixture and the manner in which the flame is stabilized. It has been observed that if the test is designed to allow fuel to collect behind obstacles in the vicinity of a hot surface, a significantly higher mass of agent is necessary for sustained suppression [1]. The superior performance of chemically acting agents such as CF_3Br and CF_3I relative to a hydrofluorocarbon alternative like HFC-125 is also accentuated in some of these tests. Full-scale testing carried out by the Navy using two different fixtures, each meant to simulate fires in the F/A-18 engine nacelle, led to different conclusions regarding the amount and relative performance of both HFC-125 and solid propellant gas generator (SPGG) fire suppressants [2].

The complexity and unpredictability of full-scale tests can be traced to two factors: flame stabilization, and agent mixing. Flame stability is governed by local geometry, surface temperature, and fuel and air flow patterns. Flame extinction will occur if the agent is entrained into the flame zone in sufficient concentration, if the fuel and air flows are disrupted enough by the agent discharge process, or by a combination of the two effects. Entrainment and localized flame stretch are, in turn, controlled by the way the fire suppression system is designed and by the location of the fire relative to the discharge nozzle.

Figure 1 shows a full-scale mock-up of an F-22 engine nacelle built by the Air Force Research Laboratory at Wright-Patterson AFB, which was used to test the suppression effectiveness of HFC-125 and SPGG as compared to Halon 1301 [3]. When the engine mock-up is slid in on its rails,

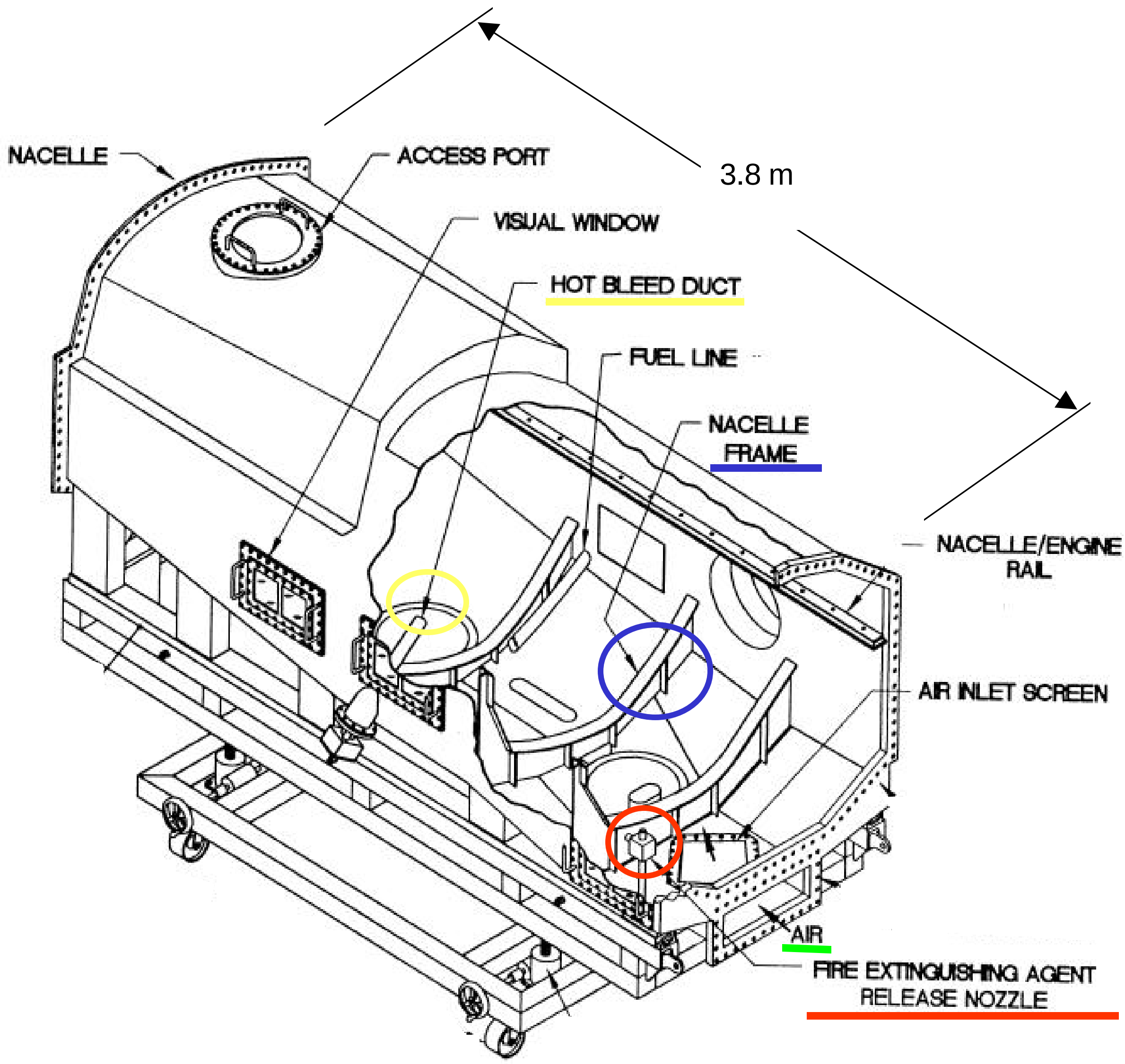

Figure 1. Full-scale F-22 Engine Nacelle Simulator at WPAFB [3, Hamins et al, 1997]

an annular region is formed about the core where flammable vapors can build and leaking fuel can accumulate. Air is brought in through a scoop at the lower right of the structure, it mixes with fuel vapor and/or a spray from a simulated leaking hydraulic, fuel or lubricating oil line, and is ignited by a spark or hot surface such as the bleed-air line. A fire can be stabilized anywhere that the fuel and air mixture is within its flammable limits and the local velocity is below the flame speed. The many obstructions in the flow formed by the nacelle frame, fuel lines, and miscellaneous equipment in the nacelle and on the engine core act as flame holders. The fire extinguishing agent is released into the nacelle near the air inlet. Depending upon the amount of agent released, the rate of agent addition, the presence of hot surfaces or electric arcs, and the location of the fire relative to the injection point, the fire may or may not be fully extinguished. An engine nacelle simulator such as the one in Fig. 1 is useful for demonstrating that a particular agent or system can successfully control full-scale fires, but it is not suited for screening the suppression effectiveness of new compounds, for ranking alternative technologies, or for gaining understanding of fire suppression physics.

Previous Studies

Agent suppression effectiveness for liquid fuel fires such as those described in NFPA 2001 is determined in a laminar diffusion flame using a cup burner [4]. Measurements of suppression effectiveness using a counter-flow burner are preferred for revealing the detailed chemical pathways in the process [5]. In either of these burners the minimum concentration for suppression is found by increasing the agent flow slowly until a critical mole fraction is achieved in the oxidizer stream and flame extinction is observed. In practice, however, agents designed to replace CF_3Br are discharged rapidly, not quasi-statically. Solid propellant gas generators, for example, typically discharge in 10 ms to 500 ms. A robust and repeatable means to evaluate the effectiveness of different formulations and application rates requires a non-conventional screening device.

Hirst and Sutton [6] developed a wind tunnel to explore the impact of step height, air flow, and pressure on the blow-out of a jet fuel pool fire stabilized behind a backward facing step. Hirst et al. [7] studied the suppression of these types of fires using various halons, and concluded that a liquid pool burning in a flow behind an obstacle is the most difficult fire to extinguish. This was born out in full-scale tests done later [8]. Experiments by Hamins et al. [9], in cooperation with Walter-Kidde Aerospace, were conducted in a wind tunnel scaled down from the earlier work by Hirst to examine the performance of HFC-125 and HFC-227ea. Investigations at the Air Force Research Laboratory [10] as part of the Next Generation Program (NGP) sought to determine the detailed structure during suppression of a non-premixed methane/air flame stabilized behind a step. The changing character of the flame with step height and air velocity was examined, along with the amount of halon 1301 required to suppress the flame as a function of the flow parameters and injection interval.

A turbulent spray burner was designed in earlier work at NIST [11] to simulate an engine nacelle spray fire resulting from a ruptured fuel or hydraulic fluid line. In this apparatus, the agent release and mixing process were well controlled and the air flow was maintained constant with a sonic orifice. This arrangement allowed the agent to be discharged without disrupting the incoming air. The turbulent spray burner was used with both gaseous and powdered agents. Hamins et al. [9] redesigned the burner to include a heated disk in the center of the flow downstream of the fuel nozzle. They showed that the concentration of nitrogen necessary to extinguish a turbulent propane flame increased substantially with surface temperature. The same trend, but to a lesser degree, was observed with hydrofluorocarbons.

Previous studies have demonstrated the effectiveness of SPGGs and their hybrids in full-scale fire suppression experiments [12, 3]. Solid propellant gas generators undergo rapid solid-phase reactions producing inert gases, principally carbon dioxide, water vapor, and nitrogen, as well as particulates composed of inorganic salts. Each component individually behaves as a fire suppressant. For many applications, particulate use is unacceptable and the SPGG hardware is typically designed to filter particulate mass during deployment. Hybrid generators are particularly attractive for some special situations such as inhabited spaces or cold temperature applications [13]. The hybrids use the hot inert

SPGG exhaust to vaporize and expel a secondary suppressant, typically a liquid, such as water or a low boiling point halocarbon, through a nozzle [12].

Objectives

The research reported here addresses the issues mentioned above for which a full-scale facility is not suited; i.e., screening the fire suppression effectiveness of new chemical compounds, ranking alternative technologies, and gaining understanding of fire suppression physics. The specific objectives put forth in the original proposal were to provide a well-characterized test fixture for screening the effectiveness of agents to suppress and prevent re-ignition of a turbulent, obstructed flame; to allow evaluation of the impact of transient agent delivery on flame extinguishment; and to provide a means to screen the effects of new and currently available agents on solid and liquid fuel surfaces.

Full funding for the three year period was to deliver the following products:

- a well-characterized bench-scale suppression screen for comparing the performance of gaseous agents and dispersed fluid mists in suppressing and preventing re-ignition of a turbulent, obstructed flame burning either gaseous or condensed fuels;
- documentation on the screen apparatus including detailed design information and experimental procedures, with round-robin testing among interested partners to insure utility of the documentation;
- an evaluation of the impact of transient agent delivery on flame extinguishment; and
- development of a means to screen the effects of new agents on condensed (solid and liquid) fuel surfaces.

The focus of the research deviated a bit from what was originally proposed, in some instances due to budget reductions and in others due to discovery.

- Solid fuels were not examined because there was no evidence that they posed a greater threat than propane in this scenario.
- A formal round-robin was not established, but work conducted during the same period at the University of Maryland (see below) and the Air Force Research Laboratory helped to support the conclusions drawn in the current study.
- The design for the liquid mist agent delivery system was not finalized due to the complexity of the process, although the general direction for such a system and its likely capabilities were revealed.
- More emphasis was placed on the deployment of an SPGG suppression effectiveness screen.

As part of the initial cost-sharing commitment, NIST gave a grant to the University of Maryland to examine fluid mechanical and heat transfer phenomena that cause an engine nacelle fire to be particularly difficult to suppress [14]. The objectives of that study were to evaluate the stability of a recirculation zone behind a backward-facing step under conditions expected in an aircraft engine nacelle, and to evaluate the effects of the flow structure on a propane diffusion flame established downstream of the step to characterize a "worst case" fire scenario. The final report from that grant is included as Appendix B to this document.

EXPERIMENTAL FACILITY

A Transient Application, Recirculating Pool Fire (TARPF) suppression facility has been developed in the current study to screen different agents and prototype systems, and as an indicator of full-scale performance. The TARPF agent suppression screen is designed to reproduce the most difficult fire situation and to allow control of critical agent discharge parameters, including agent discharge rate and duration, air flow, and obstacle geometry. The performance of gaseous agents, aerosols and solid-propellant gas generators can be examined.

Wind Tunnel and Burner

The TARPF is a small wind tunnel consisting of a number of sections, as shown schematically in Fig. 2. The main portion of the tunnel is 2.5 m long with a square cross section 92 mm on a side. (Refer to Appendix A for detailed mechanical drawings of key components of the facility.) Air, supplied by a compressor rated for a maximum flow of 180 g/s at 1.0 MPa, can be delivered to the tunnel at speeds, averaged over the 92 mm square cross section, up to 17 m/s. Flow is monitored using a calibrated sonic orifice and a piezoelectric pressure transducer. A heater is available to increase the inlet air temperature to above 200 ^oC. A honeycomb flow straightener and mixing screens are located a meter upstream of the test section. The burner consists of a sintered bronze plate, 92 mm wide by 190 mm long. Propane is the primary fuel used, which can be supplemented with a JP-8 spray. The expanded relative uncertainty* in the flows of fuel and air are $\pm$ 5 % of the measured value, based upon the manufacturers' specifications for the metering orifice and mass flow controllers.

Stainless steel baffles between 10 mm and 55 mm high are located upstream of the burner. A ramp can also be inserted to form a 25 mm high backward-facing step, as seen in Fig. 2. A 25 mm high vee-shaped obstruction can be located downstream of the propane pool to form a cavity and a second anchoring position for the flame. An ethane torch located below the vee and external to the tunnel is used to heat the surface temperature up to 900 ^oC for reignition studies. The fire is initiated by a spark across two protruding electrodes located on the side wall of the test section 20 mm above the surface of the burner and 20 mm downstream of the step. Heat release rates assuming complete combustion are up to 10 kW. The flame is viewed from above and the side through 6 mm thick Pyrex windows by a 30 Hz video camera to record the suppression process. For some experiments, a high-speed digital camera (1000 Hz) is used to investigate the flame dynamics. A photograph of the TARPF with a close up of a typical flame taken through the window is shown in Fig. 3.

Gaseous Agent Discharge

The fire suppressing agent is injected downstream of the air metering orifice. Since the air flow is choked by the metering orifice, the introduction of the agent can be accomplished without altering the total air flow. This is particularly critical when trying to distinguish chemical from physical modes of extinction. Mixing of the agent with the air is facilitated by injecting the agent through two opposed radial ports into the reduced diameter entrance region. (See Appendix A for details on the injector design.)

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* The expanded relative uncertainty on all dimensions and independent parameters described in this report is $\pm$ 50 % of the highest significant place reported, with a coverage factor of 2 [15], unless otherwise stated.

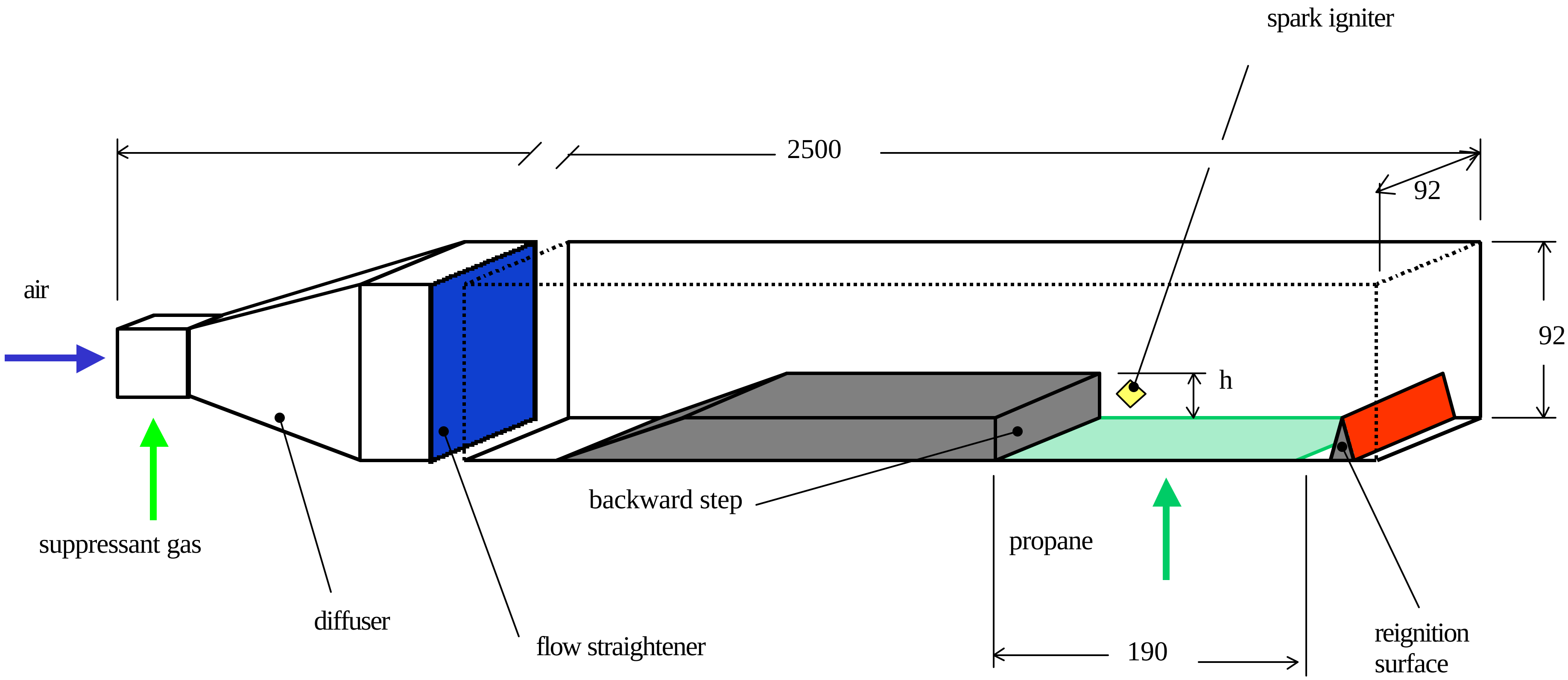


Figure 2. Schematic of step-stabilized pool fire apparatus. Dimensions are in millimeters.

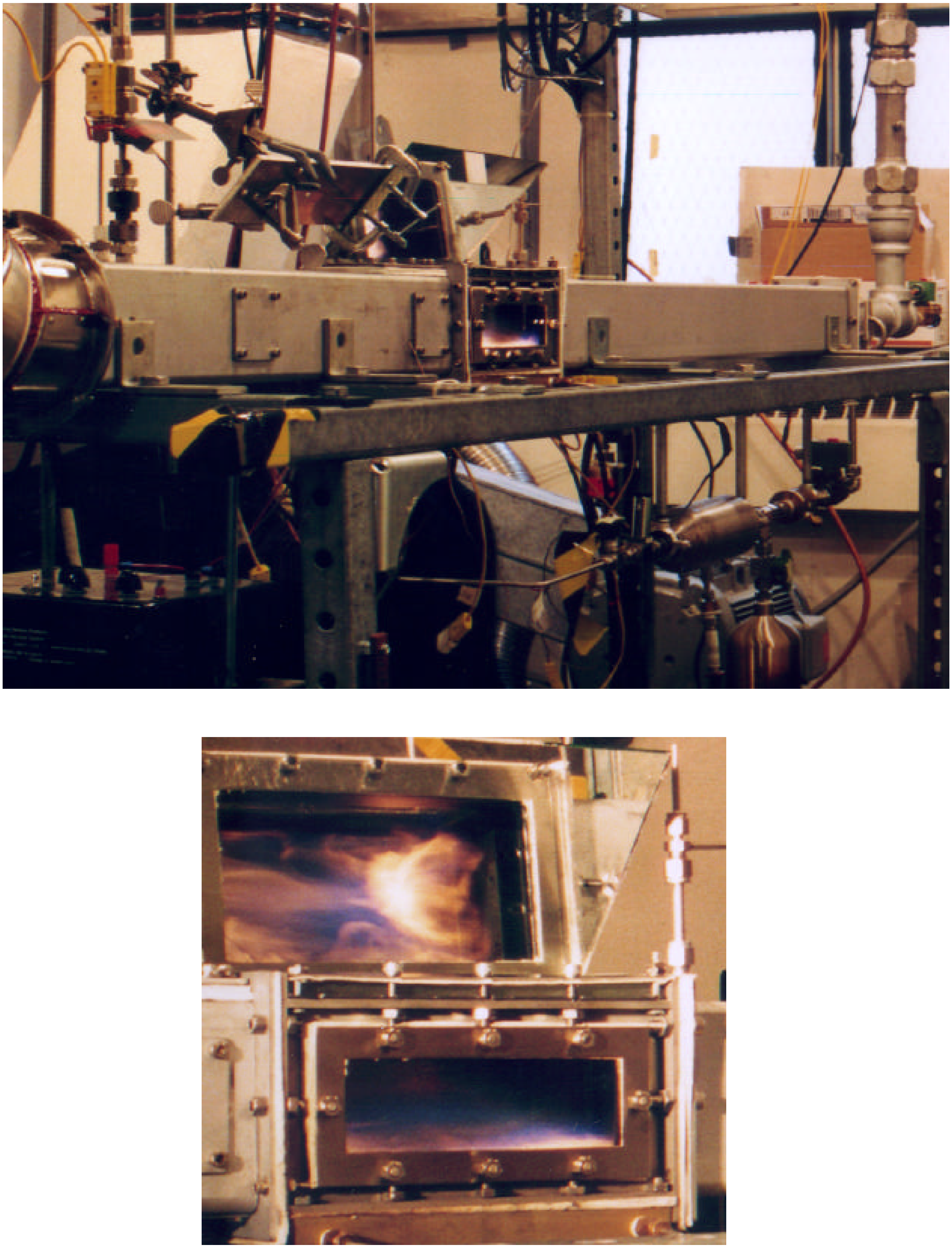


Figure 3. Photograph of TARPF with close-up of baffle-stabilized propane flame.

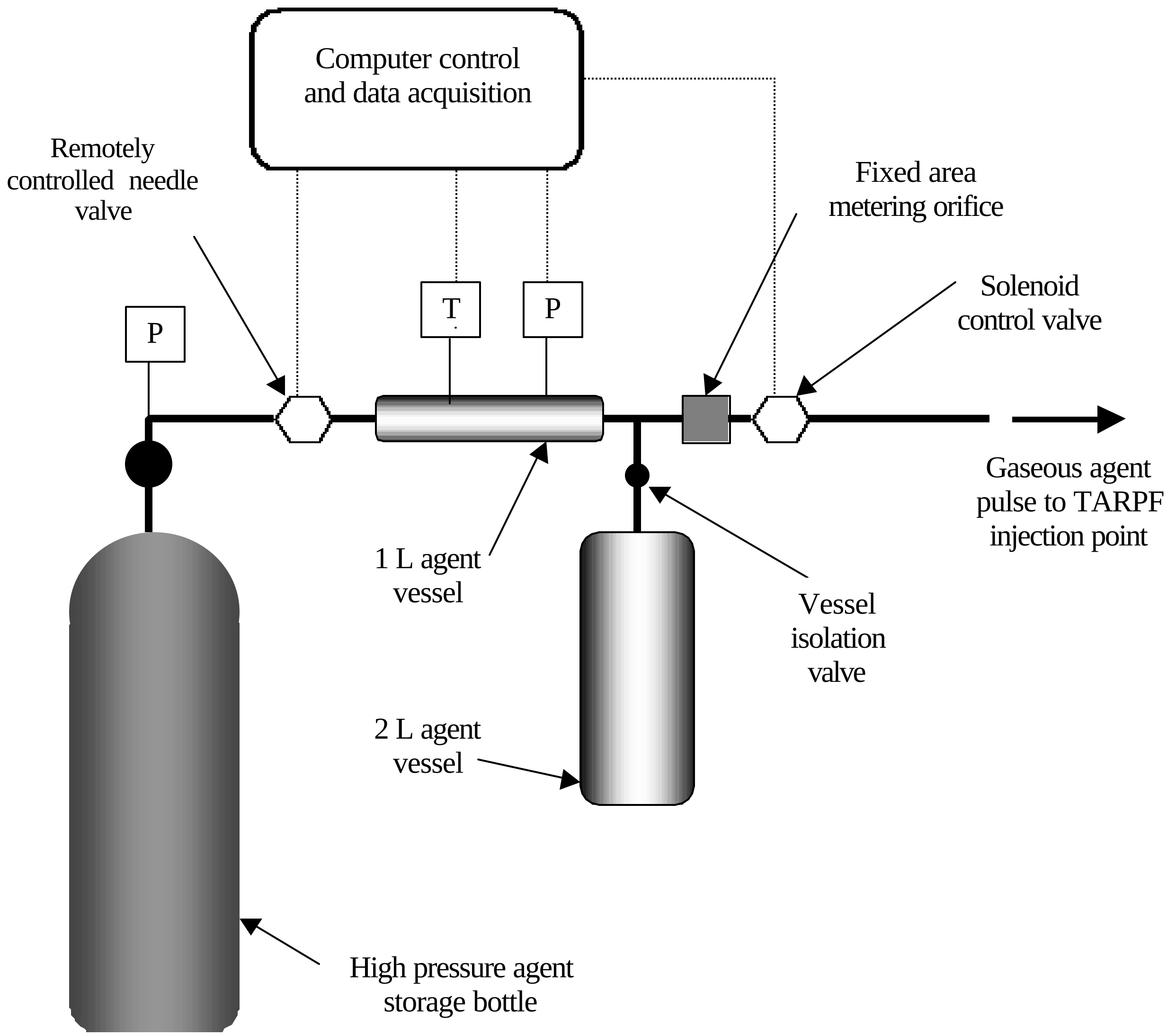


Figure 4. Schematic diagram of gaseous agent injection system.

Nitrogen (0.99995 volume fraction pure), CF_3Br (commercial grade), and HFC-125 (commercial grade) are stored as gases in one and two liter stainless steel vessels with the pressure monitored by a high-speed (1 ms response) piezoelectric transducer, and the temperature measured with a chromel-alumel (76 mm diameter) thermocouple. An electronic timer controls the interval (10 ms to 1000 ms) that a solenoid valve on the agent vessel remains open. The agent passes through a 6 mm diameter orifice before it is injected through two opposed radial ports into the air passage upstream of the diffuser. A computer monitors the flow controllers, pressure transducers, and thermocouples, and sends a signal to the electronic timer to open and close the solenoid valve while releasing the flow of suppressant. Figure 4 shows schematically the elements of the gaseous injection system.

The mass of the gaseous agent released is determined from the change in pressure and temperature in the storage vessels. The expanded uncertainty in the calculated mass is $\pm$ 2 %, with a minimum absolute uncertainty of 0.12 g attributable to the resolution of the pressure transducer. The discharge rate and duration are controlled by the initial agent pressure and an electronically actuated solenoid valve. Figure 5 is a pressure trace taken during a typical nitrogen discharge. The initial pressure is set to 0.96 MPa with an electronically controlled metering valve located between a standard high pressure nitrogen gas bottle and the stainless steel agent bottle. The computer acquires background data

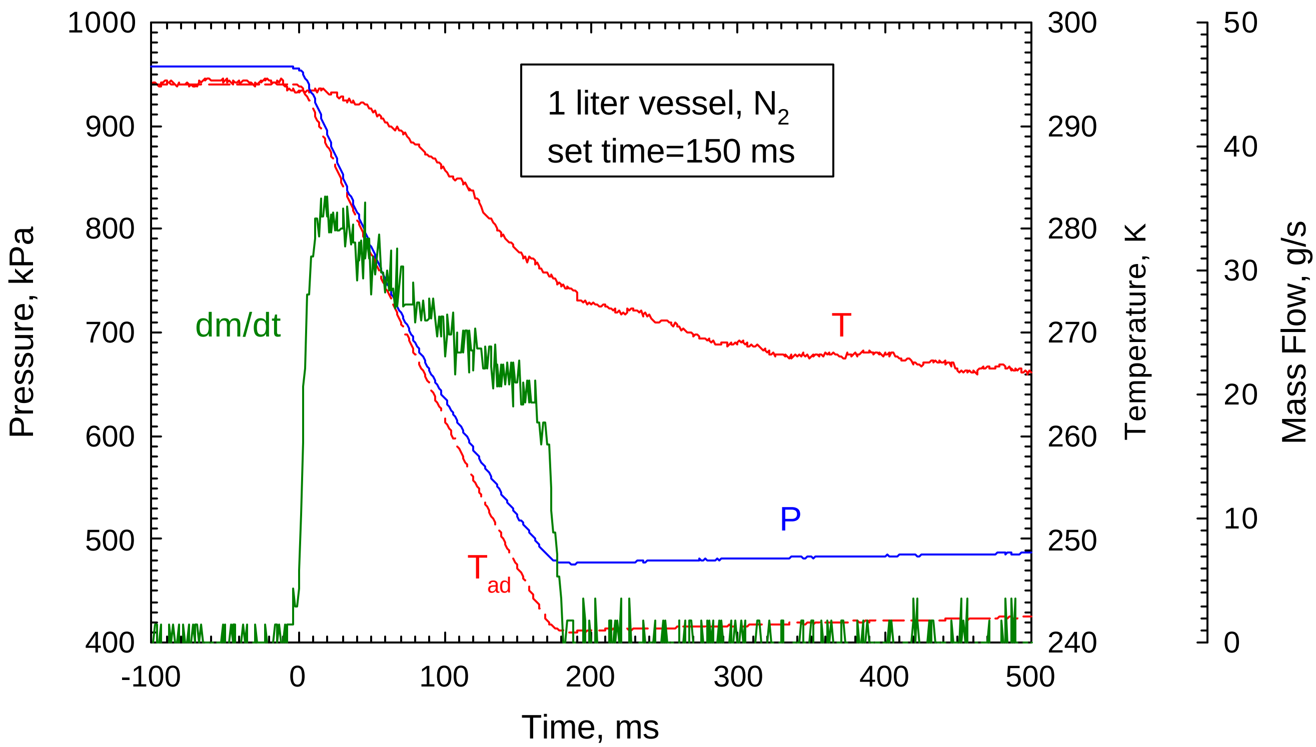


Figure 5. Storage vessel pressure trace and temperature during discharge of nitrogen into TARPF.

on the initial state for one second, at which point the electric solenoid valve is opened to allow nitrogen to enter the wind tunnel. An electronic timer closes the valve after the desired interval. Pressure and temperature in the agent bottle are measured at a frequency of 1000 Hz during the discharge process. The piezoelectric pressure transducer is able to follow the change within about 5 kPa, but the thermocouple is too slow. To determine the instantaneous mass discharge (*dm/dt* in Fig. 5), the nitrogen is assumed to be an ideal gas with the expansion inside the bottle occurring isentropically. The temperature of the thermocouple is recorded to within 1 ^{o}C. However, the actual gas temperature could differ by tens of degrees since the thermocouple bead adjusts much more slowly due to its thermal inertia. The gas temperature is more appropriately estimated by the theoretical adiabatic value, T_{ad}. Assuming errors propagate in a normal fashion, the uncertainty of *dm/dt* is estimated to be ± 2 g/s.

Three observations can be made from the shape of the discharge curve in Fig. 5: (i) the discharge data are much noisier than the pressure data, because they rely on the gradient of pressure; (ii) the measured interval (about 180 ms) is longer than the 150 ms interval set in the electronic timer, due to the inertia of the solenoid valve; and (iii) the discharge rate at the start of the process is markedly higher than the average rate.

Aerosol Agent Control

Aerosol agents require a totally different injection system than what has been described above or used previously. Yang et al. [16, 1999] developed a means to accurately meter alternative liquid agents using a nebulizer, but their screening device operated in a continuous rather than impulsive mode. Commercial

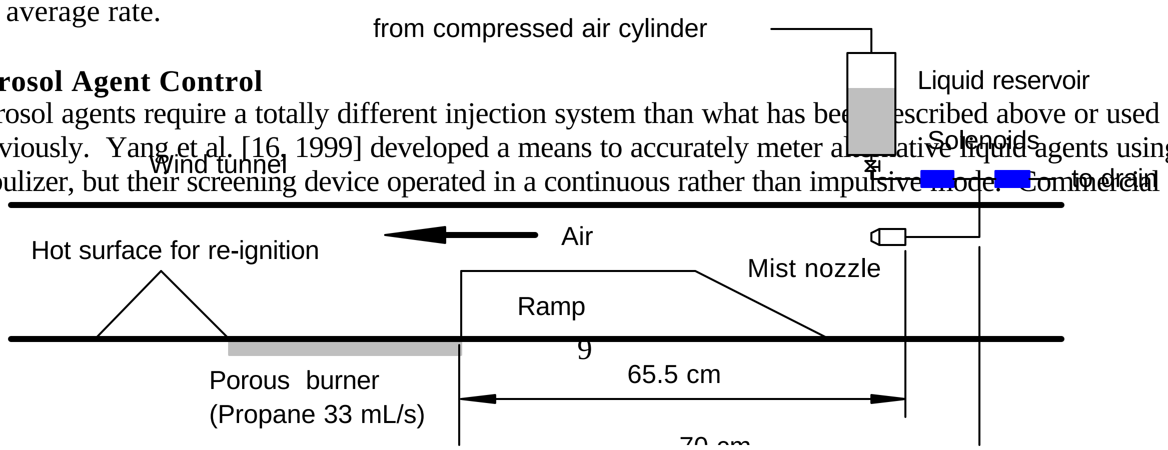


Figure 6. Liquid aerosol agent injection system.

fuel injectors were considered but the flow rates and injection duration were not adjustable over the range and with the precision necessary for the current application.

Figure 6 shows the aerosol injection system developed for the TARPF. Several kinds of atomizers were used to introduce and fully disperse misted agents into the upstream air passage under various conditions, including the introduction of aerosol at different locations along the tunnel air passage, different atomizer operating conditions such as different spray angles, liquid flow rates, and transient duration times. The liquid dispensing system consists of a liquid reservoir, a compressed air cylinder, two computer-controlled solenoids, and a hollow-cone atomizer. The atomizer was positioned equi-distanced vertically between the ramp and the upper wall of the wind tunnel, and at discrete locations along the air passage from 65.5 cm upstream of the propane porous burner to a location downstream near the ramp. Several different atomizers were used while trying to obtain a well-dispersed spray of droplets in the air passage. The atomizers were operated at line pressures that varied between 0.27 MPa and 0.69 MPa in an attempt to affect the quality of atomization. The atomizers were commercially manufactured to the following: (1) a nominal spray angle of 70° when operated at 1.03 MPa with a flow rate of 1.9 mL/s, and (2) a nominal spray angle of 60° when operated at 0.69 MPa with a flow rate of 1.1 mL/s. Operating these atomizers at nominal pressures normally results in a fully developed spray, and thus an increase above the nominal condition has a small effect on further reducing droplet size. When positioned at upstream locations, the spray appeared to fill the entire air passage cross section.

To initiate a mist for a fixed duration, the data acquisition system activated the solenoid that was connected to the reservoir. At the end of the discharge, the solenoid is deactivated to terminate the flow to the atomizer. The second solenoid leading to a drain is simultaneously activated to prevent any residual flow to the nozzle and dripping from the nozzle.

Liquid Fuel Injector/Hot Surface Arrangement

To investigate different re-ignition scenarios, a hot surface obstruction was set up immediately downstream of the propane porous burner (see Fig. 6). The vee-shaped obstruction was 25 mm in height, the base was 25 mm wide, and was centered across 50 mm of the wind tunnel passage (see Appendix A. for detailed drawings). An S-type thermocouple was place on the external upstream surface of the obstruction. A high-resistance ceramic adhesive (max: 1500 ^{o}C) was used to adhere the thermocouple to the Inconel surface, 15.5 mm thick. An ethane torch was supported underneath the obstruction to heat the inner surface to over 1100 ^{o}C. A mass flow controller was used to regulate the obstruction surface temperature. A stream of JP-8 droplets was used to provide a source of re-ignition for the propane flame by directing the droplets directly onto the heated obstruction after flame suppression. The droplet array was generated from a 0.14 mm sapphire orifice that was pressure fit into a 3.1 mm tube. The tube was inserted into the wind tunnel passage from the top wall at a position 25 mm upstream of the flame stabilizing obstacle. The end of the tube (3.8 mm) was bent 90^{o} into the direction of the air stream, and was centered between the passage top wall and face of the ramp. The JP-8 was forced through the injector with nitrogen back pressure at 170 kPa. The low back pressure and several sintered filters (with a pore size of 7   m and 2   m) were used to help prevent clogging of the injector. Initially, piezo-electric crystals were used to initiate droplet breakup, but impingement of the fuel on the heated obstruction was difficult due to entrainment of the individual droplets into the high-velocity air flow. Impingement was achieved successfully by directing the non-atomized fuel stream on the heated obstruction. The JP-8 injection time (controlled by a solenoid valve), and flow rate were varied in order to optimize the impingement process. The impingement of the fuel onto the obstruction surface resulted in a significant decrease in the surface temperature and thus care was taken to compensate for this effect during experiments.

SPGG Facility and Operation

Gas generators are manufactured in discrete units using specific chemical formulations and orifice sizes that are designed based on the particular application. Unlike a compressed gas or aerosol discharge, the TARPF operator can control neither the total mass discharged nor the injection time interval of the SPGG. To accommodate this limitation, a custom discharge chamber was designed to allow the operator to select the fraction of the SPGG discharge that is injected into the flame zone. The hardware was designed to allow standard size gas generators (which contain significantly more material than is required for suppression in the TARPF) to be evaluated by repeating the test sequence with identical gas generators and incrementally increasing the fraction of SPGG effluent allowed to flow into the TARPF air stream. The SPGG effluent (gas and particulate) passes through a metering orifice and is injected into the air stream using the same manifold as for the compressed gaseous agents. (Refer to Fig. 8a.) The flow through the bypass port is discarded into a laboratory exhaust hood. The pressure in the discharge chamber is monitored by a 1 ms response piezoelectric transducer and the temperature is measured with a 76 μm type K thermocouple. A computer monitors the pressure transducer and thermocouple.

Figure 7 shows a photograph of the TARPF and the location of the SPGG injection system; Figure 8a is a schematic diagram of the SPGG injection system; and Fig. 8b is a close-up photograph. The discharge chamber is made of stainless steel with an internal volume of approximately 200 mL. There are four main ports on the discharge chamber as seen in Fig. 8: (1) a port with a ¾ NPT female thread connecting to the gas generator cartridge holder, (2) a variable area metering orifice (1.6 mm to 6.4 mm diameter) to limit the flow into the TARPF, (3) a bypass port tapped for a 2 NPT nipple, and (4) a 19 mm port for mounting a pressure relief blow-out diaphragm. A housing made of 6 mm thick steel (seen in Fig. 8) encloses the entire injection system as a precaution against a premature or explosive discharge

Appendix A contains detailed fabrication diagrams of the discharge chamber assembly. The main chamber body (76 mm x 76 mm x 100 mm) is sandwiched between a cartridge inlet plate and a metering orifice outlet plate that limits the flow of effluent into the TARPF. Copper gaskets are used to create a seal between the plates and the chamber. Two 1/8 NPT holes on the side of the main chamber body allow access for pressure and temperature transducers. The SPGG cartridge holder (see Fig. 8) is mounted vertically facing upward to Port 1 with a 3/4 NPT nipple. The holder is made of steel pipe 229 mm long and 50 mm in diameter. The lower cap was designed to accommodate the SPGG hardware and ignition wiring. (Refer to the appendix for details.)

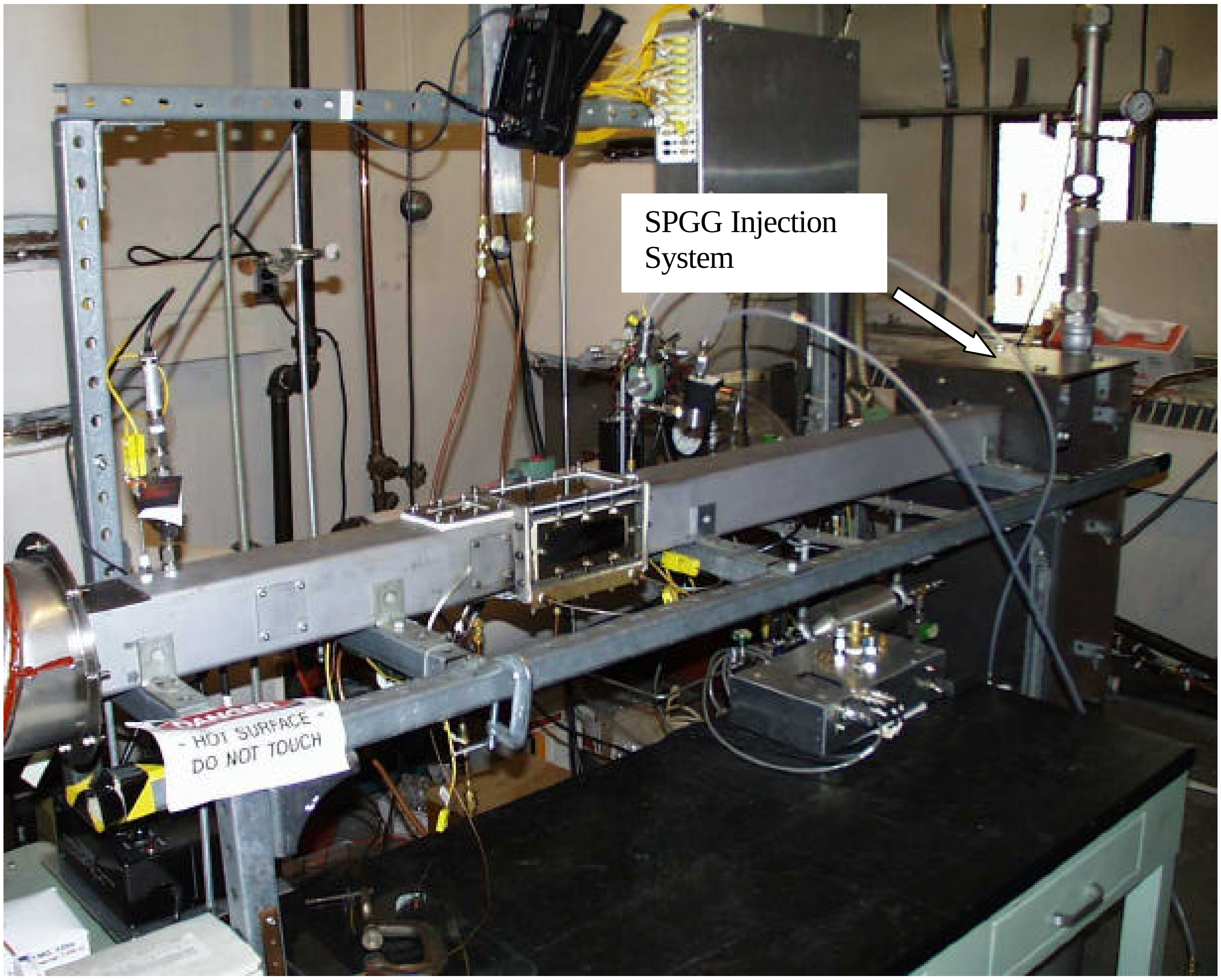
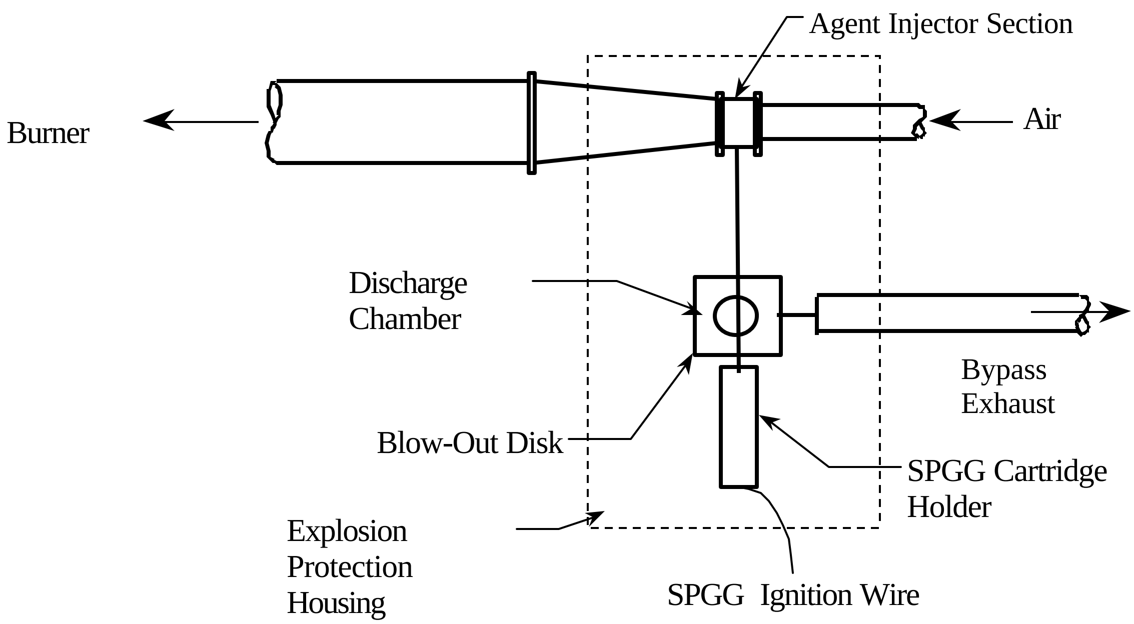


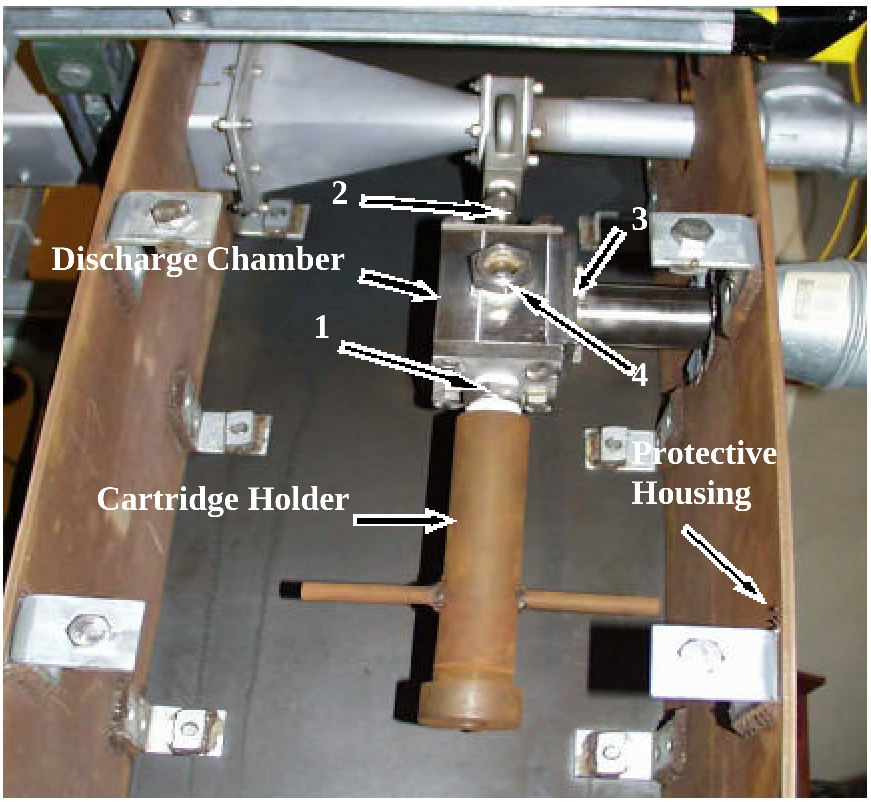
Figure 7. Photograph of TARPF showing location of SPGG injection system.

The fraction of the SPGG effluent injected into the TARPF was varied by selecting the size of Ports 3 and 4 (the pressure relief port). The combined area is referred to here as the bypass area. In an arrangement similar to that of Port 1, two plates could be attached to Port 3, allowing variation of the effective opening area (51 mm, 38 mm, or 25.4 mm). In many of the experiments, Port 4 was left open to maximize the bypass area.

The mass of the SPGG injected into the TARPF is determined from the total mass discharged and the bypass area ratio, equal to the ratio of the area of the metering orifice to the combined area of the metering orifice and the bypass area. The expanded uncertainty in the calculated mass is ± 2 %, with a minimum absolute uncertainty of 0.12 g attributable to the resolution of the pressure transducer. From the temperature and pressure measurements, the rate of suppressant addition to the incoming air, *dm/dt*, can be estimated within an expanded uncertainty of ± 2 g/s. The concentration of the SPGG in the air flow is determined from the rate of suppressant addition (*dm/dt*) and the mass flow rate of air. As in the gaseous agent experiments, the rate of air flow is invariant during the agent discharge through the use of a sonic orifice positioned upstream of the agent discharge location, in the air duct.



(a.) Schematic diagram of SPGG injection system



(b) Photograph of injection system with housing cover removed, showing the SPGG cartridge holder, discharge chamber, and ports: (1) SPGG outlet, (2) metering orifice, (3) bypass, and (4) blow-out.

Figure 8. SPGG injection system chamber.

In the current study, identical commercial air-bag hybrid gas generators were used, one in each of fifty experiments. Each generator released 20.7 g $\pm$ 0.1 g. The discharged mass was specified by the manufacturer and confirmed experimentally by weighing the generators before and after each discharge. The agent is composed of twenty grams of compressed argon gas and 0.7 g of a solid propellant, which at equilibrium converts to KCl (s) , H_2O, N_2 and a small amount of gaseous CO_2 [17].

The gas generator was discharged after steady-state fire conditions were achieved in the TARPF. The discharge was controlled by engaging an electronic switch on a control box that completed a circuit leading from a 12 V battery to the electrical connector located on the gas generator. One ampere was required to fire the 40 mg squib, which is an intrinsic part of the gas generator. The squib ignites the solid propellant, which rapidly discharges. The combustion products of the solid propellant propel the gaseous argon from the generator casing, located within the cartridge holder, into the discharge chamber. SPGG cartridges were changed and prepared for the next run in less than four minutes.

NUMERICAL MODELING AND ANALYSIS

To better understand the fluid dynamics of the suppression event, a computational fluid dynamics (CFD) model was used to simulate the baffle or step-stabilized flame in the TARPF facility. Similar numerical studies have been performed in the past few years. Among these, Liou and Hwang [18] used a two-dimensional CFD model to study the residence time of tracer particles within the recirculation zone of a backward-facing step. Weller *et al.* [19] applied a large eddy simulation (LES) model to study a premixed turbulent flame stabilized by a backward-facing step. Here, a low Mach number CFD model is applied to study the suppression event in the TARPF facility. The model is called the Fire Dynamics Simulator (FDS), and the simulations described here were performed with the first publicly released version [20]. The model is typically used to simulate large-scale fires, in which case turbulence is handled with a simple LES model. As applied here, however, the sub-grid scale turbulence model is not used, but rather the coefficients of viscosity, thermal conductivity and mass diffusivity are derived from kinetic theory and empirical extrapolation [21]. Thus, the calculations directly simulate the fluid motion (although not the combustion).

A brief description of the model equations is given below. The full numerical method used to solve the equations is given in Ref. [20]. First, consider the following conservation equations of mass, momentum and energy of a mixture of perfect gases in the low Mach number limit:

Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \qquad (1)$$

Conservation of Species

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot \rho Y_i \mathbf{u} = \nabla \cdot \rho D_i \nabla Y_i + \dot{W}_i \qquad (2)$$

Conservation of Momentum

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} \right) + \nabla p = \rho \mathbf{g} + \nabla \cdot \tau \qquad (3)$$

Conservation of Energy

$$\frac{\partial}{\partial t}(\rho h) + \nabla \bullet (\rho h \mathbf{u}) - \frac{Dp}{Dt} = (1 - \chi_r)\dot{q}''' - \nabla \bullet \mathbf{q} \qquad (4)$$

Here, ρ is the density, Y_i the mass fraction, $\dot{W}_i$ the production rate of the *i*th component of the mixture, $\mathbf{u}=(u,v,w)$ is the velocity vector, p the pressure, $\mathbf{g}$ the gravity vector, h the enthalpy, $\dot{q}'''$ the rate of heat release per unit volume, and χ_r the radiative heat loss fraction, taken as 0.20 for methane [22]. The components of the viscous stress tensor τ are

$$t_{ij} = m\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - d_{ij}\,\frac{2}{3}\frac{\partial u_k}{\partial x_k}\right) \qquad (5)$$

where m is the dynamic viscosity. The energy flux vector **q** is given by

$$\mathbf{q} = -k\nabla T - \sum_i r D_i h_i \nabla Y_i \qquad (6)$$

where k is the thermal conductivity of the mixture, T is the temperature, and h_i is the enthalpy of the *i*th component.

The conservation equations are supplemented by an equation of state relating the thermodynamic quantities r, p and h. The pressure is first decomposed into three components, a ``background" pressure p_o, a hydrostatic contribution, $-rgz$, and a perturbation to the hydrostatic, $\tilde{p}$. The coordinate z is the vertical spatial component. Using this definition of pressure, the equation of state can be written in a form appropriate for a perfect gas in the low Mach number regime [23]:

$$p_0 = \rho T \mathcal{R} \sum (Y_i/M_i) = \rho T \mathcal{R}/M \qquad (7)$$

Here, M_i is the molecular mass of the *i*th species, M is the average molecular weight of the mixture and R is the universal gas constant. The pressure p in the state and energy equations is replaced by the background pressure p_o to filter out sound waves that travel at speeds that are much faster than typical flow speeds expected in fire applications.

A further assumption about the thermodynamic variables is that the constant-pressure specific heat of the *i*th species $c_{p,i}$ is assumed to be independent of temperature. Under this assumption, the enthalpy can be written as:

$$h = \sum_i h_i Y_i = T \sum_i c_{p,i} Y_i \qquad (8)$$

The specific heat for each species can be expressed in terms of the number of internal degrees of freedom active in that molecule.

$$c_{p,i} = \left(\frac{2+\nu_i}{2}\right)\frac{\mathcal{R}}{M_i} = \left(\frac{\gamma_i}{\gamma_i - 1}\right)\frac{\mathcal{R}}{M_i} \qquad (9)$$

If the ratio of specific heats for all the species is assumed to be that of a diatomic molecule $(n = 5, g = 7/5)$, the equation of state can be rewritten in the form:

$$p_0(t) = \frac{\gamma - 1}{\gamma}\rho h \qquad (10)$$

The basis of this approximation is that nitrogen will be the dominant species in the simulations.
The coefficients of viscosity, thermal conductivity and material diffusivity are approximated from kinetic theory. The viscosity of the *l*th species is given by

$$\mu_l = \frac{26.69 \times 10^{-7}(M_l T)^{\frac{1}{2}}}{\sigma_l^2 \, \Omega_v} \qquad \frac{\mathrm{kg}}{\mathrm{m\ s}} \tag{11}$$

where s_l is the Lennard-Jones hard-sphere diameter (Å) and Ω_n is the collision integral, an empirical function of the temperature *T*. The thermal conductivity of the *l*th species is given by

$$k_l = \frac{\mu_l \, c_{p,l}}{\mathrm{Pr}} \qquad \frac{\mathrm{W}}{\mathrm{m\ K}} \tag{12}$$

where the Prandtl number Pr is 0.7. The viscosity and thermal conductivity of a gas mixture are given by

$$\mu = \sum_l Y_l \, \mu_l \quad ; \quad k = \sum_l Y_l \, k_l \tag{13}$$

The binary diffusion coefficient of the *l*th species diffusing into the *m*th species is given by

$$D_{lm} = \frac{2.66 \times 10^{-7} T^{3/2}}{M_{lm}^{\frac{1}{2}} \sigma_{lm}^2 \, \Omega_D} \qquad \frac{\mathrm{m}^2}{s} \tag{14}$$

where M_{lm}=2(1/M_l+1/M_m)$^{-1}$, $s_{lm} = (s_l + s_m)/2$, and Ω_D is the diffusion collision integral, an empirical function of the temperature *T* [21]. It is assumed that nitrogen is the dominant species in any combustion scenario considered here, thus the diffusion coefficient in the species mass conservation equations is that of the given species diffusing into nitrogen:

$$(\rho D)_l = \rho \, D_{l0} \tag{15}$$

where species 0 is nitrogen.

A simple one-step, finite-rate reaction is used to model the combustion of propane:

$$C_3H_8 + 5\ O_2 \longrightarrow 3\ CO_2 + 4\ H_2O \tag{16}$$

The fuel depletion rate (unit mass / unit time / unit volume) is given by the expression

$$\dot{W}_{C_3H_8} = -\frac{B}{M_{O_2}} \rho^2 \, Y_{C_3H_8}^a Y_{O_2}^b \, e^{-E/RT} \tag{17}$$

The heat release rate term is

$$\dot{q}''' = -\dot{W}_{C_3H_8}\,\Delta H \tag{18}$$

where ΔH is the heat of combustion. Westbrook and Dreyer [24] suggest values for propane of $B = 8.6\times10^{11}$ cm^3 mol^{-1} s^{-1}, E=126.6 kJ/mol, a=0.1 and b=1.65 for propane. The heat of combustion is assumed to be 46,400 J/g.

Both two and three-dimensional simulations have been performed. The advantage of the two dimensional calculations is that greater spatial and temporal resolution can be exploited. The disadvantage is that the much of the complex structure of the turbulent flame cannot be simulated. Three-dimensional calculations are much costlier to perform, but yield a great deal of information about the flame structure.

The solution of the conservation equations governing the flow in the tunnel is computed on either a two-dimensional, uniformly-spaced grid spanning a plane 552 mm long and 92 mm high, or a three dimensional, uniformly spaced grid spanning a volume 552 mm long, 92 mm wide and 92 mm high. The number of the grids are 576 by 96 and 256 by 48 by 60, respectively. The backward-facing step is approximated with masked grid cells. The reactant flows consist of oxygen, nitrogen and propane. Nitrogen is used to represent the products of combustion simply to reduce the computational time. Propane is introduced into the flow domain through a 190 mm by 92 mm vent in the floor of the tunnel at a uniform rate of 33 mL/s. Air and agent are introduced into the domain 100 mm upstream of the step with a top hat velocity profile. At the outflow boundary a constant ambient pressure is assumed. Ignition is achieved by momentarily heating up a small patch on the floor of the tunnel just downstream of the step. At all other wall locations, the temperature is maintained at 200 ^{o}C.

Presented in Fig. 9 are sequences of images separated in time by 0.01 s that are taken from simulations that illustrate the dynamics of the suppression event. Figure 9a is a 2-D simulation of flow (moving left to right) over a 25 mm step. The darkness of the image reflects the extent of local heat release. Figure 9b is a 3-D simulation of a flame stabilized on a 25 mm baffle that is undergoing a successful suppression. In both Figs. 9a and 9b the top images show the flame just prior to discharge of nitrogen into the air stream. Upon injection, the flame is disturbed by a large vortex generated by the pressure pulse. Due to the low Mach number approximation, the gas upstream of the step is essentially incompressible, and the velocity jump from 2.1 m/s to 5.7 m/s is conveyed to all points in the flow domain in 0.02 s, the time of the ramp-up from the base velocity to the injection velocity. Thus, even before the agent arrives at the step, the flame has already been dramatically transformed from its original state. The generation of the large vortex at the step produces a pathway by which the agent can penetrate the region just behind the step, mixing with the gases, cooling and diluting the fuel and oxygen.

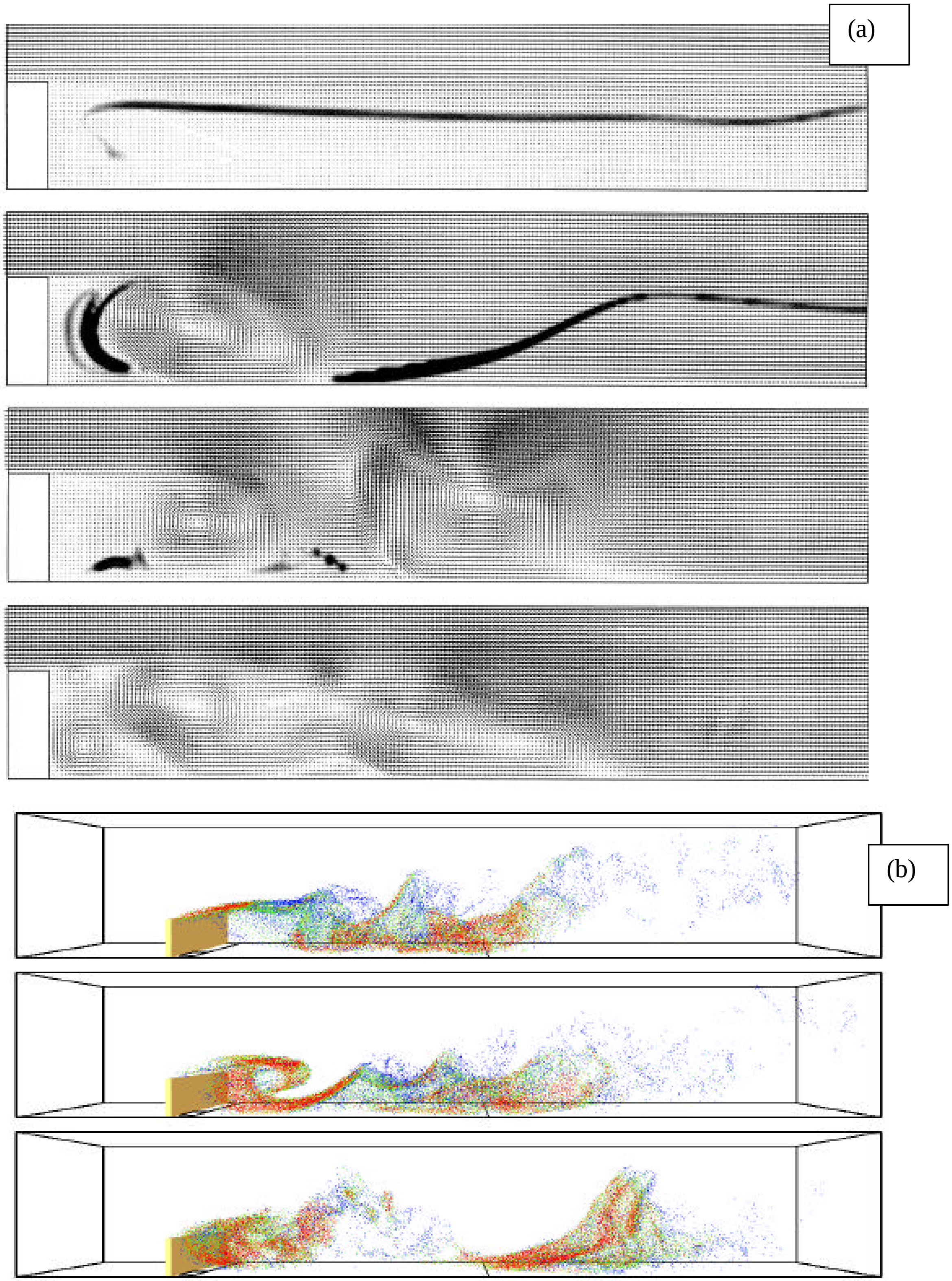


Figure 9. The disruption of a stabilized flame by the injection of nitrogen upstream of 25 mm high obstacle: (a).2-D simulation of flow over step; (b) 3-D simulation of flow over baffle (frames are separated by 0.01 s).

EXPERIMENTAL RESULTS

Flow Characterization

The facility was operated over a range of propane and air flows to examine the flame behavior. Blow out can be achieved either by increasing the air flow or decreasing the propane flow. At low air velocities, a fluctuating laminar flame is anchored on the top downstream edge of the step or baffle and extends well downstream of the porous plate. As the velocity increases, the flame becomes turbulent and less luminous. Near blow-out, the orange color disappears and the visible blue flame shrinks. With the backward-facing step installed, an average air velocity above the step of over 23 m/s is necessary to blow out the flame if the propane flow is greater than 33 mL/s (corresponding to a transverse velocity of 1.9 mm/s).

Two air flows were chosen to evaluate the ability of the agents to suppress the propane pool fire stabilized by the backward-facing step. The low and high mean air velocities (just above the step) were 2.1 m/s $\pm$ 0.2 m/s and 5.4 m/s $\pm$ 0.2 m/s, respectively. Corresponding propane flows of 33 mL/s $\pm$ 2 mL/s and 85 mL/s $\pm$ 2 mL/s, respectively, were utilized. The low flow condition corresponds to what Takahashi et al. [10] describe as regime I suppression (rim-stabilized flame), and the high flow is transitional between regimes I and II (intermittent turbulent flame).

The velocity distribution of the air 76 mm upstream of the burner was measured with a 3 mm diameter pitot tube at seven locations across the duct. Figure 10 compares the results with and without the flame present for the high flow condition. The velocity profiles are seen to be flat within 5 % over the central three-fourths of the duct. The boundary layer above the step appears to be less than 7 mm thick. The presence of the flame tends to increase the pitot probe signal, which is likely due to a combination of preheating the air upstream by the flame, acceleration in the flow due to partial blockage of the duct caused by the expanding combustion gas, and a possible shift in electrical output due to heating of the pitot probe and transducer.

The facility is designed to introduce suppressant impulsively without altering the air flow. This is achieved by maintaining a choked condition for the air independent of modest changes in downstream pressure generated by the injection process. The pitot tube was used to measure the instantaneous flow 76 mm ahead of and 5 mm above the backward step during the discharge of C_2HF_5 into the air stream for the two different air flow conditions (without fuel flowing). The dashed lines in Fig. 11 show the combined effect of the velocity (*V*) and density (ρ) change, $V(\rho/\rho_o)^{1/2}$, created by the injection process, where ρ_o is the initial density of the air stream. Figure 11a is for the low air flow condition and a high rate of agent discharge; Fig. 11b represents a high air flow with a low rate of agent addition. The pressure, *P*, in the agent storage vessel is also plotted in Fig. 11, from which the rate of C_2HF_5 mass added, *dm/dt*, is calculated. The injection interval is 130 ms $\pm$ 5 ms for both cases, but the amount of agent added in Fig. 11b is 1/3 the amount added in Fig. 11a because the agent storage volume was 1 L and 3 L, respectively.

The sizable increase in $V(\rho/\rho_o)^{1/2}$ seen in Fig. 11a within 0.10 s of the passage of the acoustic wave results from the slug of air between the injector and the pitot tube being shifted downstream by the addition of agent. High-speed video images of the flame during the discharge corroborate this description. The shift is barely discernable in Fig. 11b since the amount of agent added is small relative to the flow of air. The time that the agent itself arrives at the pitot tube is limited by the bulk convection and the distance the probe is downstream of the point of injection (1.1 m). The times of arrival of the agent at the pitot tube can be estimated to be 0.58 s and 0.24 s for the conditions in Figs. 11a and 11b, respectively. Interpretation of the pitot signal is complicated by the much higher density of C_2HF_5 as compared to air.

An instrument developed by Pitts et al. [25] was used to measure the infrared absorption by C_2HF_5 at a wavelength of 8.7 μm $\pm$ 0.1 μm. Figure 11 also contains a plot of the absorptance,

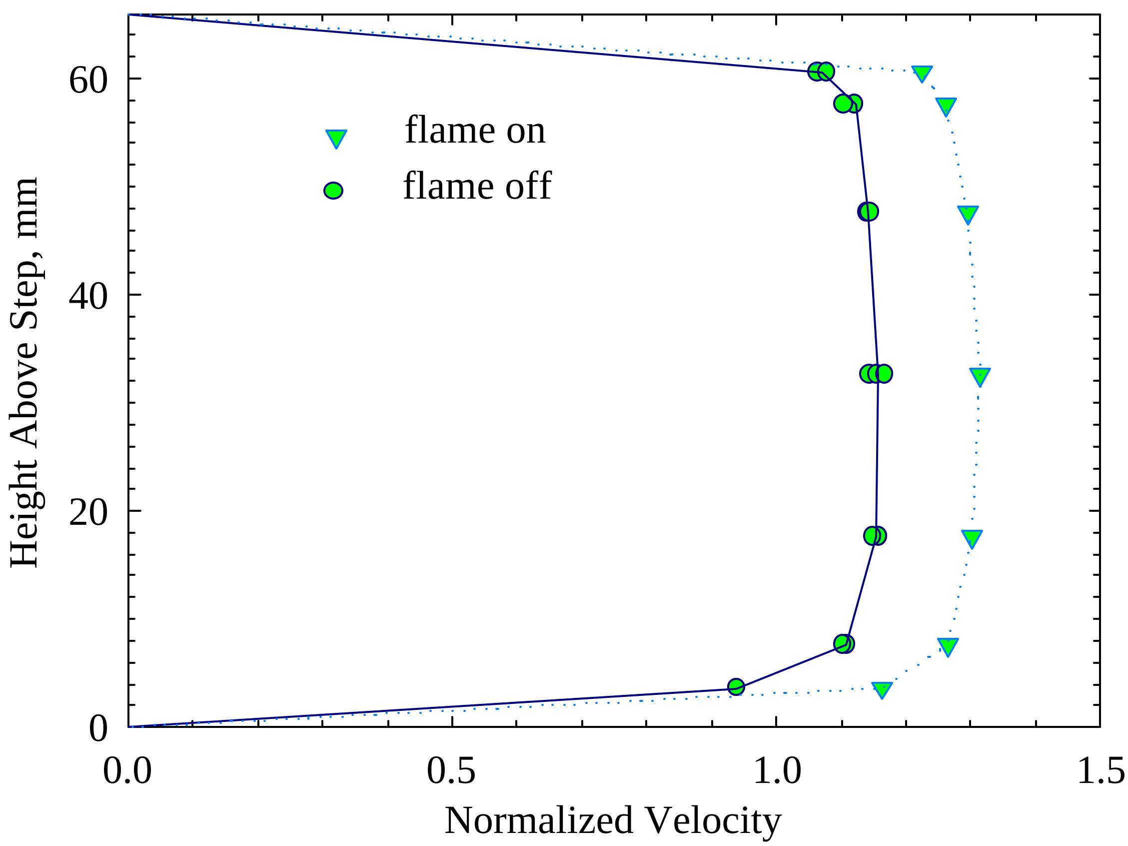


Figure 10. Velocity (normalized by nominal mean) measured upstream of burner, with and without flame lit.

integrated across the width of the duct, during the discharge. The viewing port is 2.3 m downstream of the agent injector and 1.1 m downstream of the pitot tube. The absorptance pulse in Fig. 11b is similar in shape to the rate of discharge, but about 0.1 s wider. Nonuniform mixing of the agent with air as it flows over the step and into the recirculation zone contributes to the long absorptance tail that is evident for over a second in Fig. 11a, although the agent injection duration was only 0.13 s.

The amount of suppressant necessary to extinguish a fire in the TARPF depends upon the fuel and air flows chosen to challenge the suppressant. Figures 12 and 13 show how the amount of nitrogen necessary to extinguish a 25 mm baffle-stabilized flame varies with the flow of air and fuel. The uncertainty in any given value is estimated to be ± 0.2 g. The filled circles in the figures indicate extinction and the crosses represent no extinction. When the air speed is less than 5 m/s and the fuel flow is fixed at 45 mL/s ± 2 mL/s, decreasing the speed (see Fig. 12) reduces the amount of nitrogen necessary to extinguish the flame. No flame extinction occurred between 5 m/s and 15 m/s because the amount of nitrogen necessary exceeds the maximum amount contained in the storage vessel. Above 16 m/s, the strain on the flame is sufficient at times to extinguish the flame without the need for any nitrogen. (The dashed lines are included in the figure to assist the eye in identifying the extinction boundaries.)

The propane flow does not have much affect on the amount of nitrogen needed to extinguish the flame if the injection interval and air flow are fixed, as shown in Fig. 13. There is a lower limit for the propane (<12 mL/s) that leads to extinction due to heat loss to the burner, even with no nitrogen dilution. The upper limit of propane (120 mL/s) is dictated by the maximum safe operating temperature of the burner; however, since the mass of nitrogen needed to suppress the flame does not

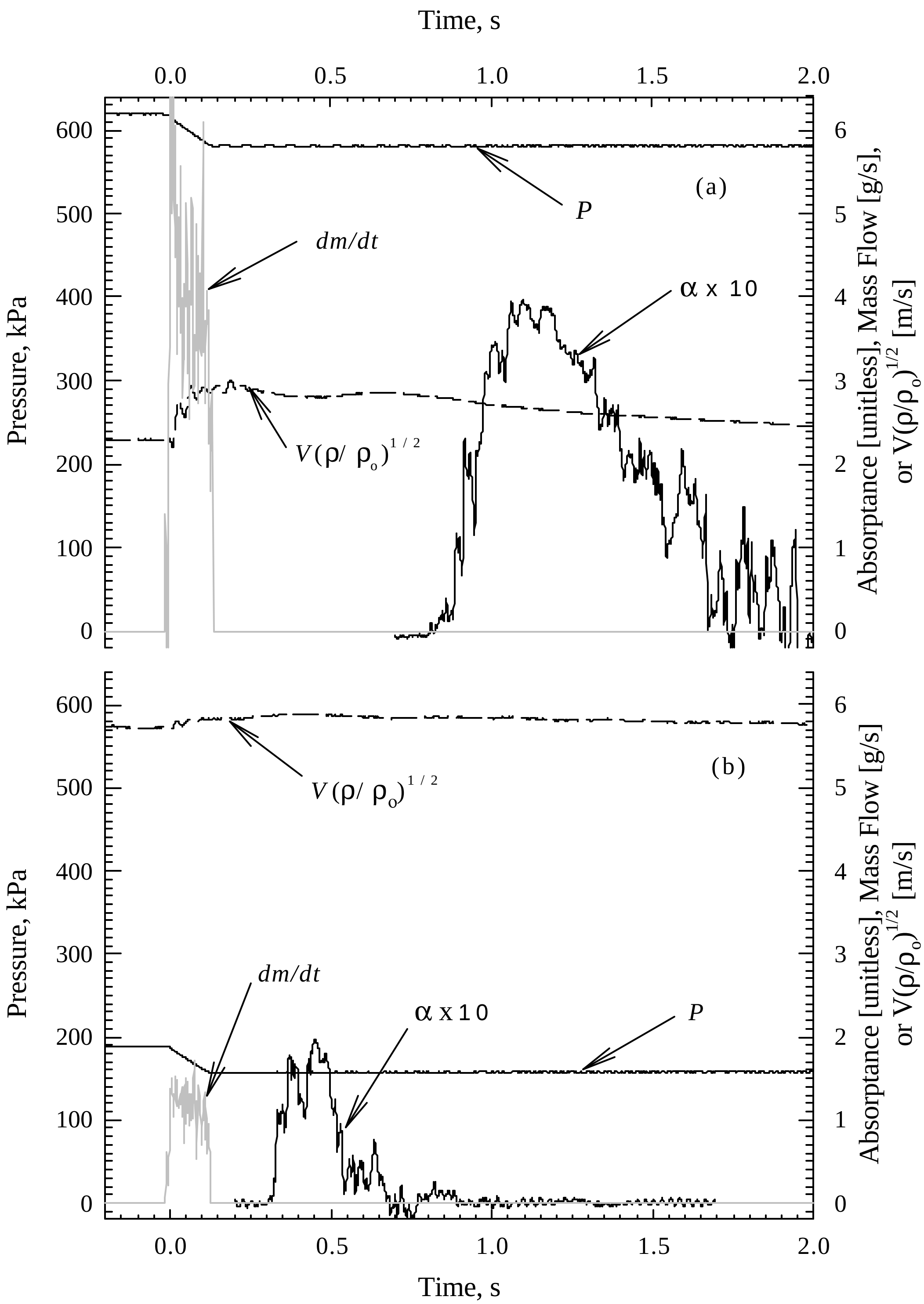


Figure 11. Bottle pressure, agent mass flow, velocity above step, and IR absorptance 1 m downstream of step during 0.125 s discharge of C_2HF_5; (a) low air flow, high agent flow, (b) high air flow, low agent flow.

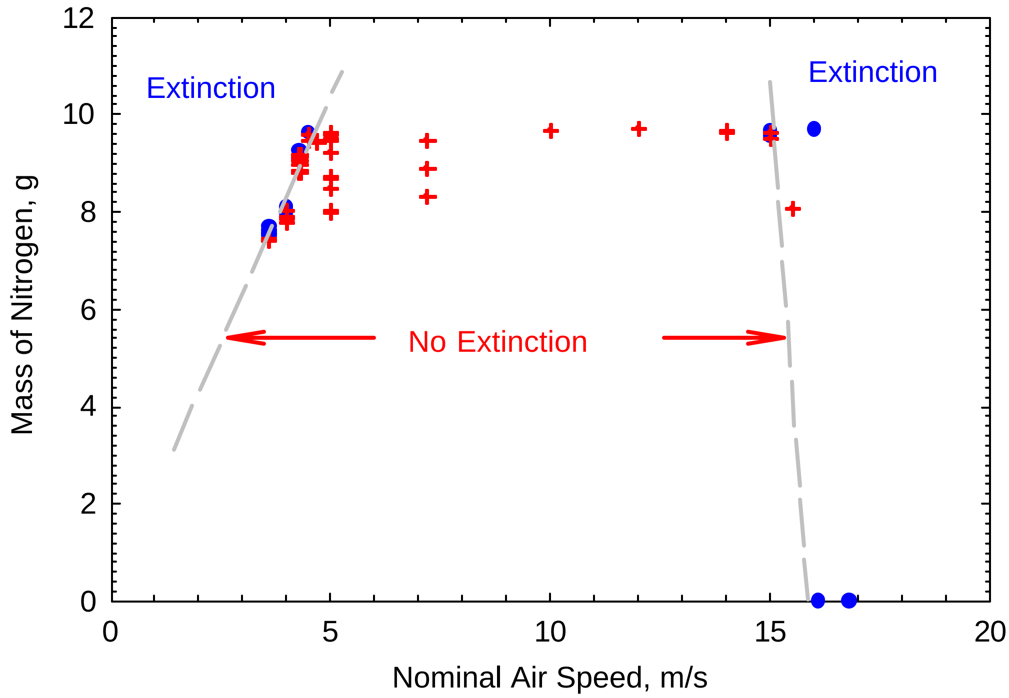


Figure 12. Impact of air speed on extinction of 25 mm baffle-stabilized flame; propane flow is 45 mL/s, nitrogen injection time is 312 ms: circles imply extinction, crosses imply no extinction.

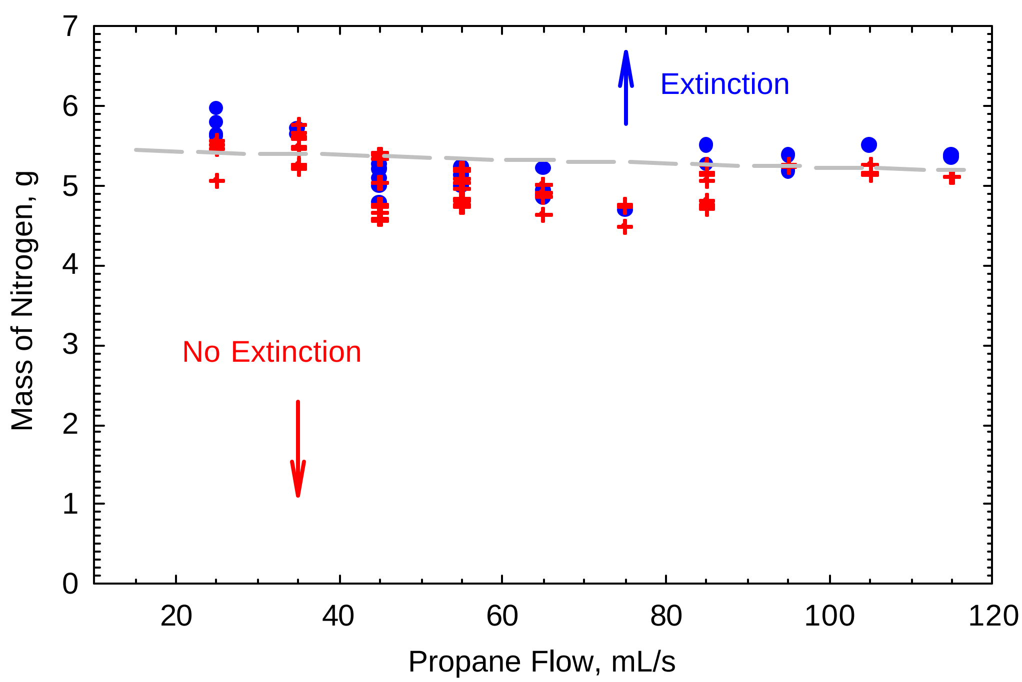


Figure 13. Impact of propane flow on N_2 required for suppression of 25 mm baffle-stabilized flame; air flow is 3.88 m/s, injection time is 185 ms; circles imply extinction, crosses imply no extinction.

appear to increase, there is no need to operate the burner at higher fuel flows. (Note: the dip in mass required for propane flows around 75 mL/s is attributed to the low number of experiments conducted in this region.)

The relationship between the total mass of nitrogen required for suppression and the injection time interval is plotted in Fig. 14 for a 3.9 m/s $\pm$ 0.2 m/s air flow, 45 mL/s $\pm$ 2 mL/s propane flow flame stabilized on the 25 mm baffle. The open symbols are experiments that did not extinguish the flame, and the closed symbols are experiments that led to extinction. (The total number of experiments conducted exceeds by a factor of ten the number of data points plotted in this and the following curves; for clarity, only those conditions close to the extinction boundary are included.) As the injection interval increases from 100 ms to 500 ms, the minimum mass required increases over three-fold. The rate of mass addition (calculated by dividing the total mass by the estimated injection interval) decreases with increasing injection interval, as shown in the right-hand figure.

Effect of Obstruction Geometry

The data plotted with squares in Fig. 15 were taken with the ramp placed in front of the 25 mm baffle to form a backward step-stabilized flame, rather than the simple baffle-stabilized flame represented in Fig. 14. The air flow is the same in these two cases but the propane flow is higher, 85 mL/s, in Fig. 15. The addition of the ramp and increase in propane flow do not have much influence on the mass of nitrogen required for suppression. For both the baffle and backward step, just under 6 g of N_2 are required when the injection interval is 200 ms $\pm$ 10 ms. The data plotted as circles in Fig. 15 were taken with the nominal air speed reduced to about 1.5 m/s and the propane flow reduced a proportionate amount to near 33 mL/s. The squares in Fig. 15 represent experiments conducted at the high air and propane flows, and circles represent experiments conducted at the lower flows. Open symbols indicate that the flame was not extinguished, and filled symbols indicate flame extinction. Less than 4 g $\pm$ 0.2 g of N_2 are needed to extinguish this flame if injected over a 200 ms $\pm$ 10 ms interval. The differences in rates of mass addition to suppress the high flow and low flow flames can also be seen at the right in Fig. 15.

Figures 16 and 17 show what happens to the required nitrogen mass and addition rate if the baffle height is decreased to 10 mm or increased to 55 mm (blockage from 11 % to 60 %), respectively. The symbols have the same meaning as in Fig. 15. The short baffle produces a fire which is the easiest to extinguish, and the high baffle the most difficult in terms of the amount and rate of N_2 addition.

The effect of baffle height is not large if the injection interval is at least 150 ms, as can be seen more clearly in Fig. 18. (Note that 6 mm has been added to the height of each obstacle to account for the distance between the floor of the tunnel and the recessed top surface of the burner.) The bottom curve delineates the minimum amount of nitrogen for suppression when the air flow is fixed at its high value and the agent injection interval is maintained at 175 ms $\pm$ 10 ms. The open circles represent the largest mass of N_2 that did not result in extinction for flames stabilized on the different sized baffles; the filled circles are the minimum mass of agent that successfully extinguished the flames. The diamonds are the results for the 25 mm baffle with the ramp in place (backward-facing step). Experiments were also conducted with and without the reignition obstruction shown in Fig. 2. The amount of N_2 necessary for suppression was unchanged.

The rate of mass addition is plotted in the upper curve of Fig. 18 (the triangles are the backward-facing step, and the squares are for the baffles). The data are plotted two ways: the higher value is the rate of nitrogen addition computed during the first 50 ms that the solenoid valve is open (refer to the shape of the *dm/dt* curve in Fig. 5); the lower value is the average over the entire open interval measured from the pressure trace. The estimated rate of mass addition varies substantially, especially for the 55 mm baffle, depending upon whether the averaging period is the first 50 ms or the entire time that the solenoid remains open.

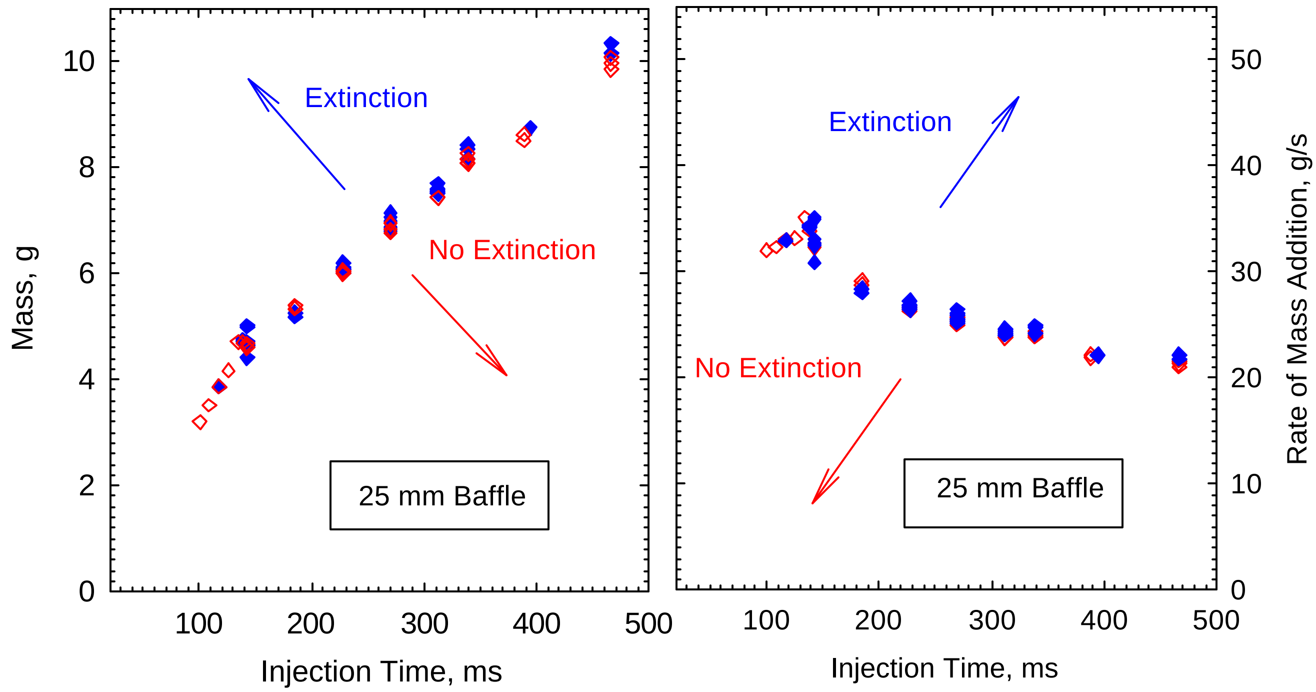


Figure 14. Mass and rate of nitrogen addition required to extinguish 3.88 m/s air flow, 45 mL/s propane flame: filled diamonds, extinction; open diamonds, no extinction.

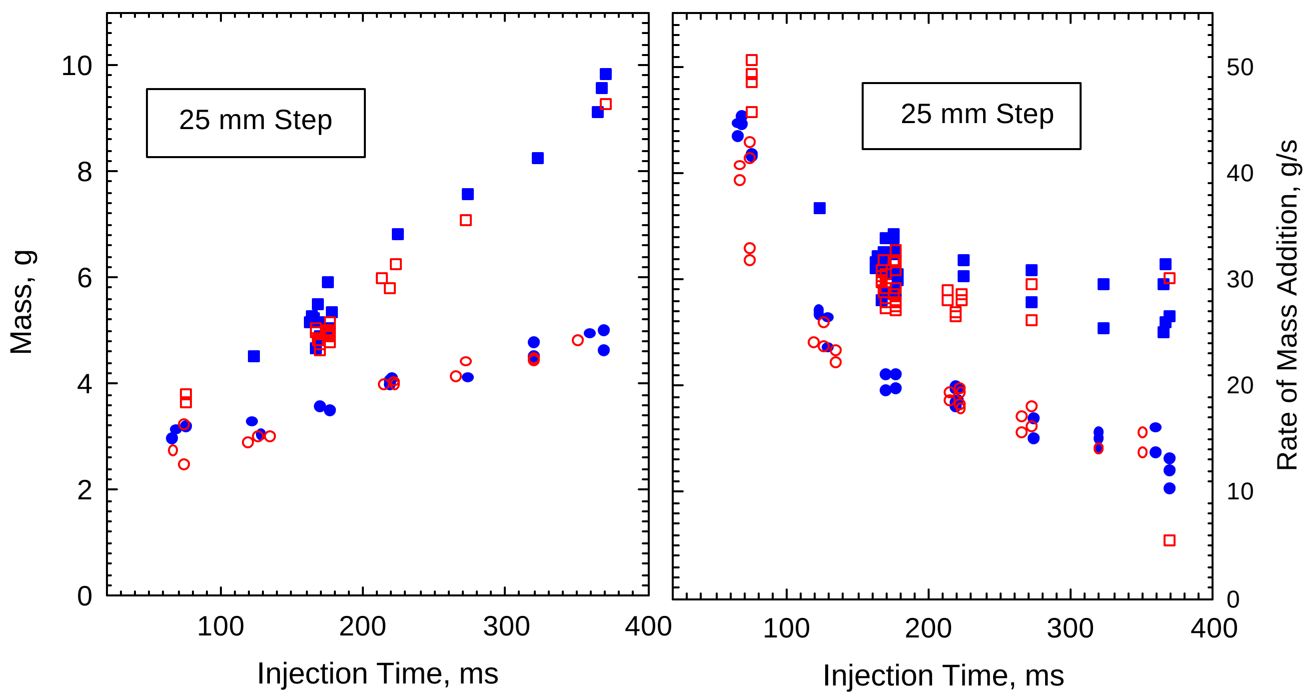


Figure 15. Mass and rate of nitrogen addition required to extinguish high flow (squares) and low flow (circles) air/propane flames: filled symbols, extinction; open symbols, no extinction.

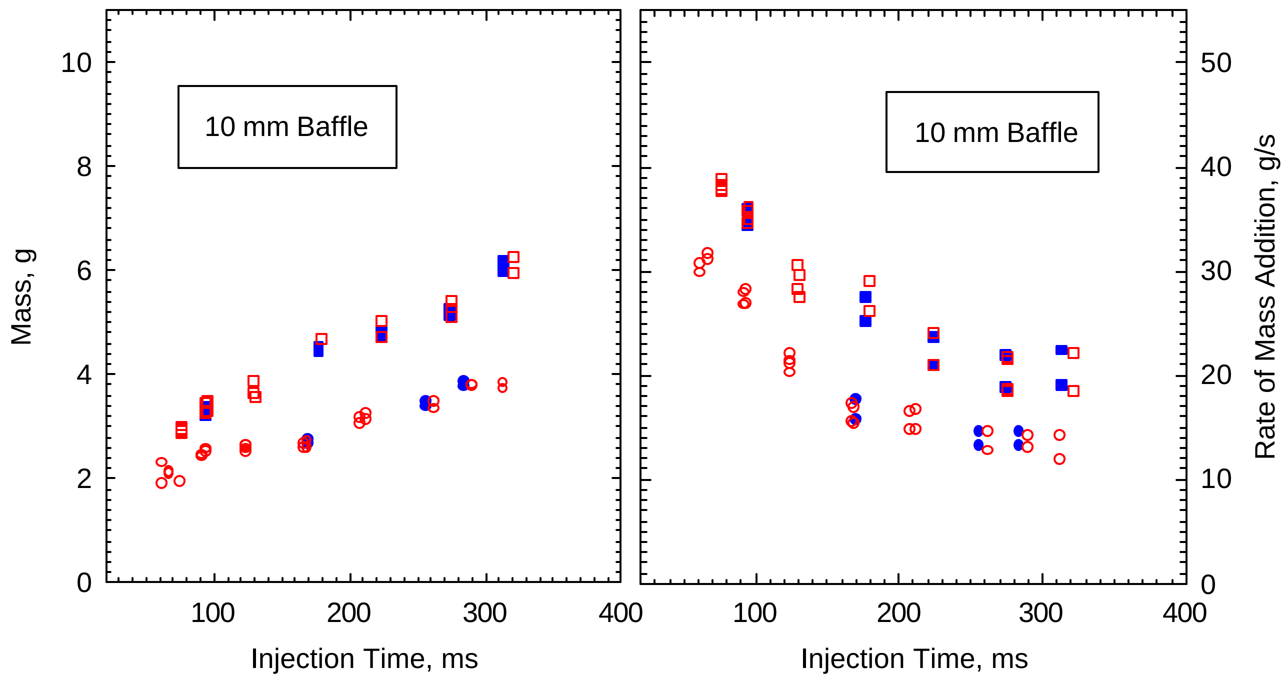


Figure 16. Mass and rate of nitrogen addition required to extinguish high flow (squares) and low flow (circles) air/propane flames: filled symbols, extinction; open symbols, no extinction.

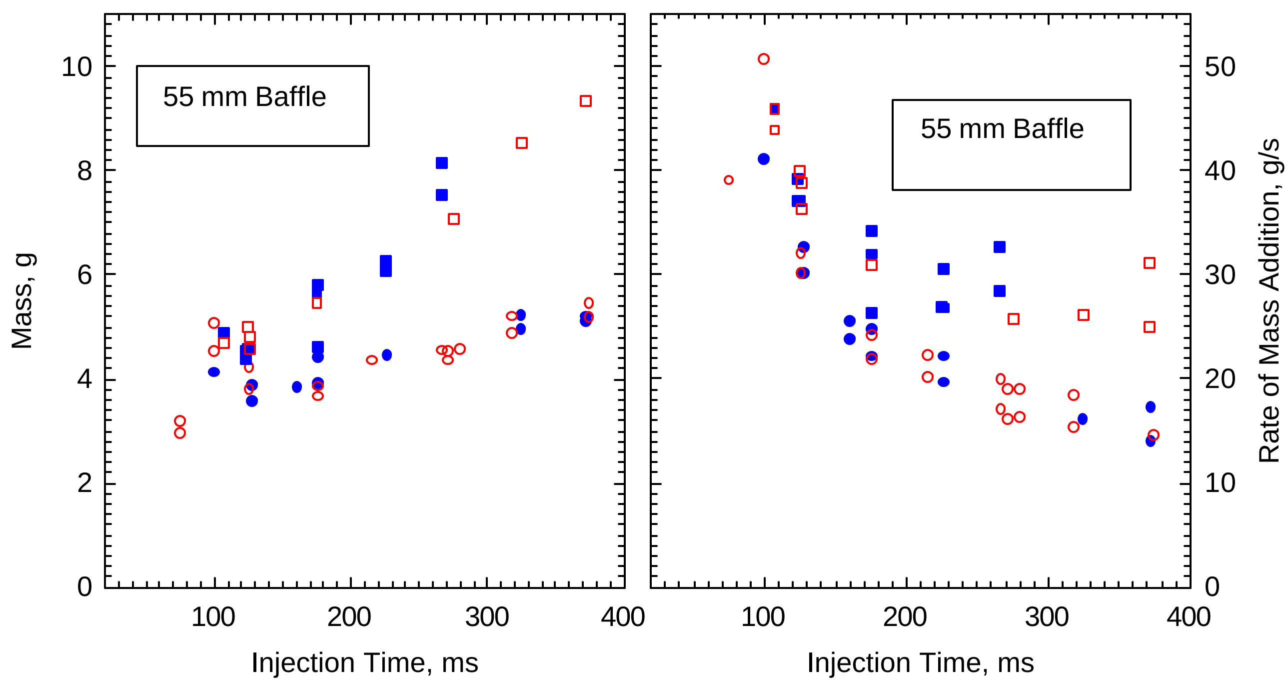


Figure 17. Mass and rate of nitrogen addition required to extinguish high flow (squares) and low flow (circles) air/propane flames: filled symbols, extinction; open symbols, no extinction.

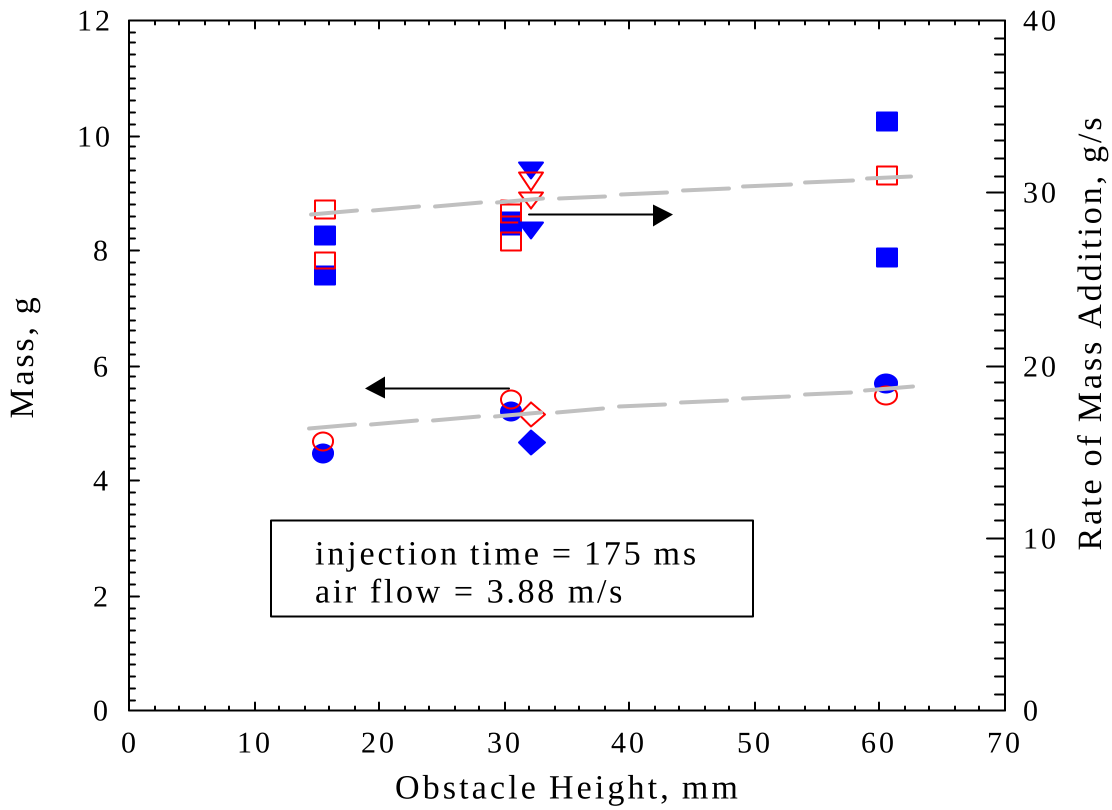


Figure 18. Impact of obstacle height on the total mass and rate of addition of nitrogen required to suppress obstacle stabilized pool fire.

Effect of Type of Gaseous Agent

Figure 19 is a plot of the minimum agent mole fraction that extinguished the fires (χ) as a function of the agent injection time interval (Δt) for both N_2 and CF_3Br. The parameter χ is defined as the average volume flow of agent during the injection interval divided by the sum of the agent and bulk air flows. The data represent experiments conducted over a range of conditions including air velocities (defined above the obstacles) that varied from 2 m/s to 9 m/s, propane flows from 33 mL/s to 85 mL/s, and baffle heights between 10 mm and 55 mm, in addition to the 25 mm backward step. The open and closed symbols represent the low and high air flow conditions, respectively. Figure 19 shows that χ decreases with increasing injection time interval for all obstacle types and both agents. The highest mole fraction requirements were consistently for the low air flow conditions. For some experiments, the value of χ was nearly 0.8 for short injection intervals. The most challenging geometric configuration was the 55 mm baffle, followed by the 25 mm obstacles, and the 10 mm baffles. There was little difference in χ between the 25 mm step, 25 mm cavity and the 25 mm baffle and those data are presented as one group in Fig. 19.

The effectiveness of CF_3Br was compared to that of N_2 using the 25 mm high backward step. The 1 L storage vessel was used to accentuate the pressure change associated with the small quantities of CF_3Br required for suppression. Only 1.6 g ± 0.2 g of CF_3Br injected for 100 ms was needed to extinguish the flame under the high air flow conditions (corresponding to $\chi \cong 0.075$), as compared to 3.9 g ± 0.2 g for N_2 as agent ($\chi \cong 0.5$) under similar conditions. These results are consistent with numerous studies that show that CF_3Br is a more effective suppressant than N_2 for both free standing and baffle stabilized flames.

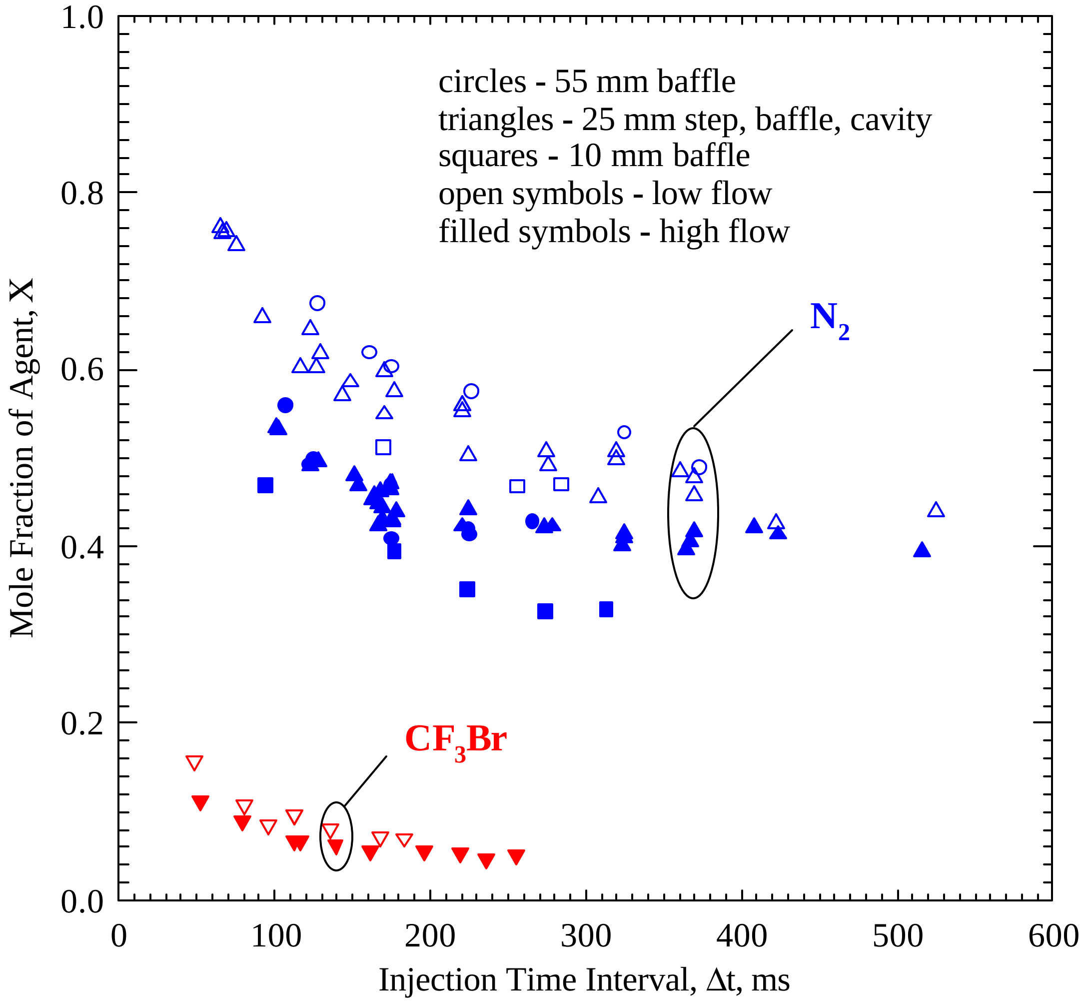


Figure 19. Mole fraction of agents (N_2 and CF_3Br) added to air at extinction boundary for high and low flow conditions, as a function of the injection time interval and obstacle geometry.

Aerosol Agents

The aerosol injection system described earlier was used by Pitts et al. [26] to compare the suppression performance of a water mist and methoxynonafluorobutane in the TARPF to that measured in the steady-state Tsuji burner [16]. The air flow in the tunnel was fixed at 6.67 x 10^{-3} m^3/s and the porous burner was operated at a propane flow rate of 33 mL/s. The mist discharge duration was varied from 1 s to 10 s. The mass flow rate of the liquid agent, $\dot{m}_{agent}$, can be calculated using the density of the liquid and the calibrated volume flow rate. The mass fraction of the liquid agent, b_{agent}, in the air stream is then

$$b_{agent} = \frac{\dot{m}_{agent}}{\dot{m}_{agent} + \dot{m}_{air}} \qquad (19)$$

where $\dot{m}_{air}$ is the calculated mass flow rate of air. Note that in writing Eq. (19), it is implicitly assumed that the mist droplets are homogeneously dispersed in the carrier phase (air).

A number of suppression experiments were run with the mass fraction of the water calculated to be 0.11. The pool fire stabilized behind the backward-facing step of the ramp could not be completely suppressed under these conditions, although useful observations could be made. Before the mist injection, the flame was luminous and yellow. During the mist injection, the yellow flame was nearly extinguished with pockets of localized blue flame regions. The mist was also observed to have high momentum, which resulted in the major portion of the mist bypassing the flame completely. The duration of the small blue flames coincided with that of the mist application. Once the mist application period was over, the flame regained its original burning intensity and yellow luminosity.

The above observations indicate partial localized flame suppression due to sufficient droplet entrainment into some portions of the mixing layer, but an insufficient number of droplets entrained over time to prevent the flame from flashing back into the previously extinguished zones. In flow experiments conducted with no flame present, the droplets were observed to traverse the burner very rapidly with little entrainment of the mist into the recirculation zone. With a flame, gas expansion effects are enhanced and are expected to further carry the droplets axially past the flame. Although the droplet statistics were not measured, one would expect that the size distribution from these atomizers would cover a range between 1 μm and 200 μm. For droplet entrainment into the recirculation zone behind the ramp to occur, a high concentration of micrometer-sized droplets needs to be dispersed throughout the passage cross section and entrained in the air flow. Apparently, a large enough concentration of small droplets (with a small relative velocity) was unavailable to suppress the flame completely.

In the Tsuji burner experiments, Yang et al. [16] used a droplet delivery system that assured efficient transport of fine liquid droplets to the flame. They found that a calculated water mist mass fraction of 0.03 in the air stream was sufficient to extinguish their laminar counter-flow flame. This is less than 1/3 the mass fraction of water injected into the TARPF without achieving suppression. Thermodynamic estimates of the cooling effect of water suggest that a mass fraction of almost 0.13 is required to bring the equilibrium temperature of a propane/air flame down to 1500 K, which is the extinction temperature found by Pitts et al. [25] for purely thermal agents. Thus, one could argue that a 0.11 mass fraction should not be expected to suppress the TARPF flame.

More experiments and computational modeling are necessary to sort out the discrepancy between the TARPF and Tsuji results to identify the relative importance of droplet entrainment, size distribution, and transient vs. steady-state effects on the mass fraction of water needed to ensure flame extinction. This may best be achieved using an ultrasonic humidifier (producing all droplets less than 2 μm), or twin-fluid atomizer, to inundate the recirculation zone with submicron droplets, as long as the droplets do not pre-vaporize before reaching the flame. Note that entrainment of droplets into the recirculation zone will be dependent on determination of the Stokes number, $St = rD^2DU/18md$, where r is the droplet density, DU is the relative velocity between the droplet and surrounding air, m is the air viscosity, and d is a characteristic size of a vortex structure formed by the air stream. For values of $St < 1$, droplets will be dispersed with the surrounding stream while for large values of St insufficient time will be available to influence the droplet motion. Thus, entrainment will be optimized for smaller droplets that have little relative velocity to the airflow.

SPGG Results

For the SPGG experiments, the nominal velocity of the air above the backward-facing step was maintained constant at 5.4 m/s; the propane flow was 85 mL/s (at standard temperature and pressure). The pressure build-up in the discharge chamber was measured for a range of bypass areas, as seen in Fig. 20. The high pressures produced in the SPGG discharge chamber and the known area of the metering orifice allow the mass flow of agent added to the air stream of the TARPF to be estimated by assuming that the flow through the orifice is choked. Figure 21 shows the repeatability of the agent injection process with five overlaying mass flow and thermocouple temperature traces. (The thermocouple does not reflect the true gas temperature, which is expected to be hundreds of degrees Celsius hotter than recorded in the figure.)

The SPGG discharge time was consistently 20 ms ± 1 ms, which is over three times faster than the shortest N_2 or CF_3Br injection interval, and not much affected by the bypass port area. The bypass ratio (A_{in}/A_{tot}) is the area of the inlet metering orifice (port 2) divided by the total open area available for flow to exit the discharge chamber (ports 2, 3, and 4) The time interval, Δt, is shown in Fig. 22 as a function of the estimated discharge mass. The total mass delivered to the air stream during the discharge process is found by integrating *dm/dt* over Δt. Excluding the highest and lowest area ratios, the estimated mass delivered can be seen in Fig. 22 to be linearly proportional to the area ratio; however, almost 50 % more mass is estimated than one would expect. The dashed line in Fig. 22 indicates that a 1-to-1 relation would exist if the mass were directly proportional to the area ratio.

There are several factors that contribute to an uncertainty in the estimate of the absolute mass of agent. First, uncertainties in the gas composition and temperature upstream of the metering orifice affect the estimate since the mass is proportional to the square root of the molecular weight divided by the temperature. A factor of two under-estimate in this parameter would cause a 40 % over-estimate in mass, which, if corrected for, would cause the data plotted in Fig. 22 to more closely align with the dotted line. A second source of uncertainty is the complexity of the flow within the discharge chamber created by the jet emanating from the SPGG. The calculation assumes that the upstream flow is steady and parallel to the axis of the metering orifice, but the flow is highly transient and more perpendicular.

Suppression of the propane pool fire with the hybrid gas-generators was found to be successful if at least 1.5 g of agent was injected into the fire; conversely, extinction never occurred when less than 0.7 g was added. The percent of the fires suppressed varied when the agent mass was between these limits, as shown in Fig. 23. The suppression statistics were generated by lumping the mass from thirty-three discharges into bins 0.2 g wide, centered about the data plotted. The solid line is a fit to the data assuming that the shape is sigmoidal. It is apparent from the curve that there is a 50 % chance that suppression will be successful if the amount of agent is 0.9 g ± 0.1 g, and there is a 90 % success rate for 1.3 g ± 0.1 g of agent.

Figure 24 is a plot of the mass of agent required for suppression versus the injection time interval. All of the SPGG data are lumped around 20 ms since the injection time was fixed. The N_2 and CF_3Br results extend to much longer injection time intervals. Linear fits to the data yield intercepts of 1.6 g for nitrogen and 1.2 g for halon 1301. The SPGG data fall close to the halon results. The significance of the linear shape and the value of the intercept is unclear; however, the superior performance of the gas generator is undeniable.

The mass fraction of agent, β, is defined as the total mass injected divided by the injection duration, Δt, over the sum of the mass flow of air plus the mass flow of agent. The percentage of occasions that the flame was extinguished is plotted in Fig. 25 as a function of β. All of the fires were extinguished when β was greater than 0.62; none for a mass fraction below 0.49. The definition of β for the SPGG differs somewhat from the definition as applied to the gaseous agents because the mass discharge profiles for SPGG and the gaseous agents are different. Whereas the mass injection rate of the gaseous agents is controllable through selection of the injection hardware, the SPGG mass injection rate is practically dependent on the propellant effluent generation rate (i.e., the propellant burning rate). The character of the mass injection rate, *dm/dt*, is qualitatively different than that of the gaseous agents. Its value for the SPGG is best represented by the pressure profile shown in Fig. 20, as compared to *dm/dt* seen in Fig. 5 for gaseous N_2. For the same mass, variation of the discharge profile will lead to variation in agent effectiveness. Optimization of the rate of agent discharge is an area that would benefit from further study, which could be approached from analytic, numerical, and experimental perspectives.

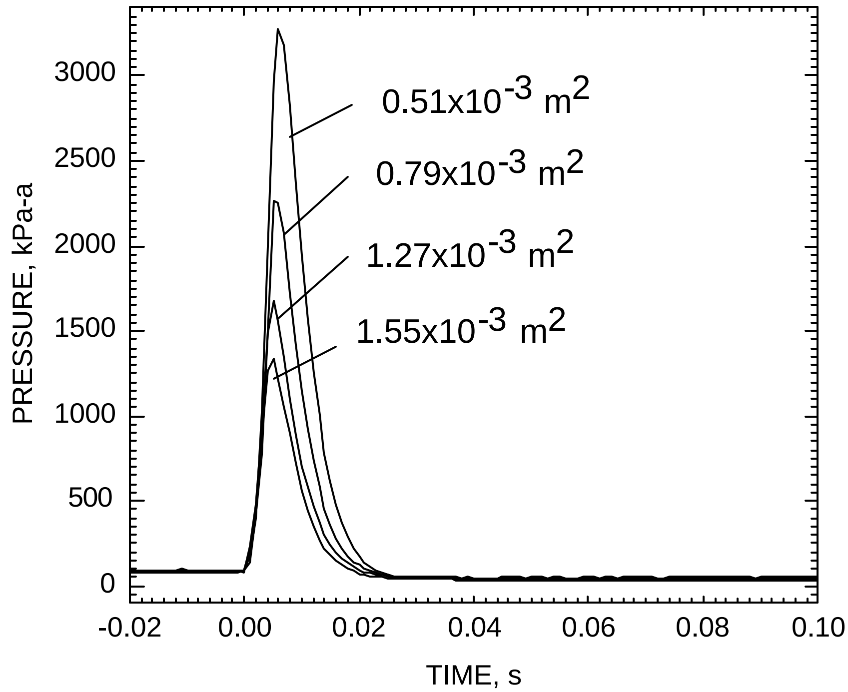


Figure 20. Chamber pressure created by SPGG discharge as a function of bypass area.

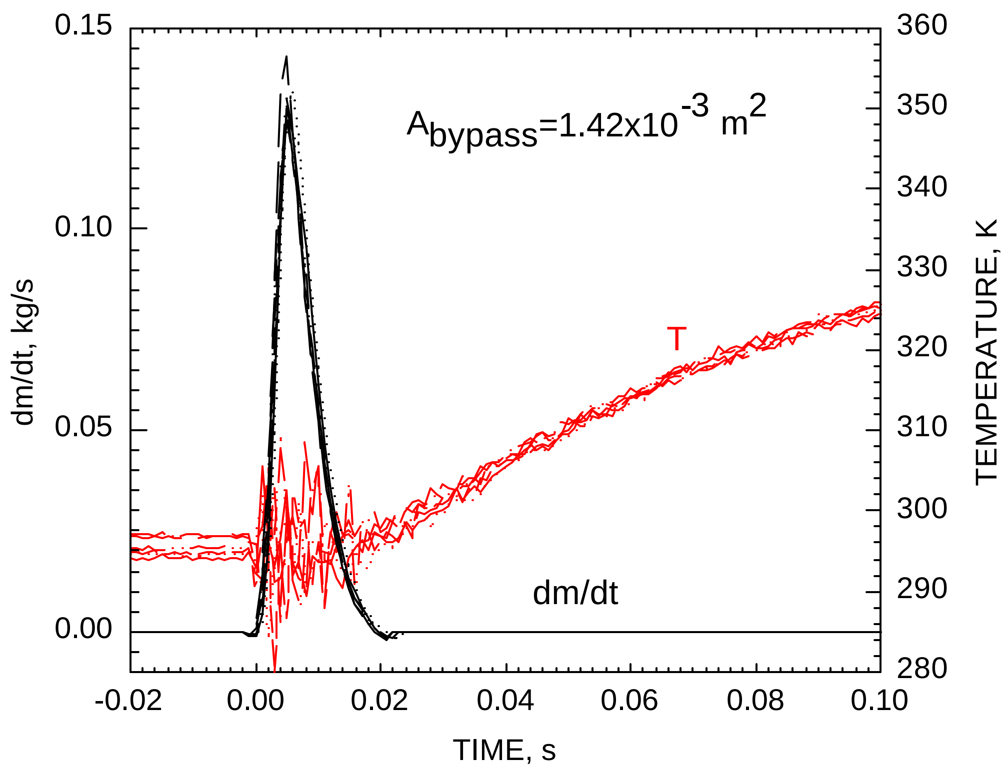


Figure 21. Discharge chamber thermocouple temperature and estimated mass flow of SPGG efluent added to air stream for multiple identical runs.

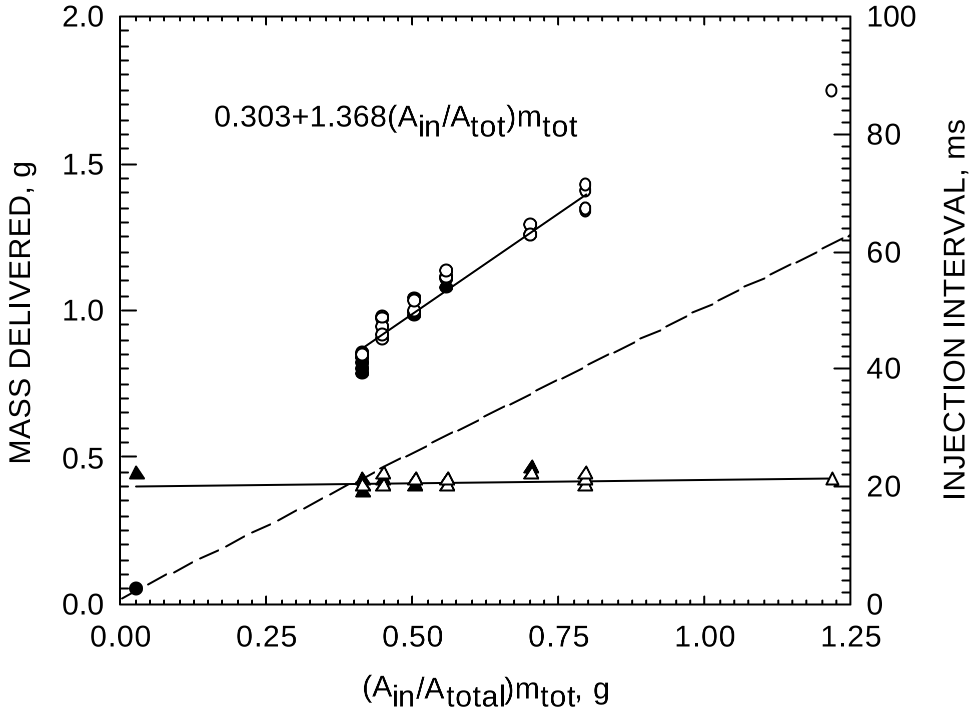


Figure 22. Injection interval (triangles) and calculated mass delivered to flame (circles) as function of area ratio times total mass of gas generated (20.7 g).

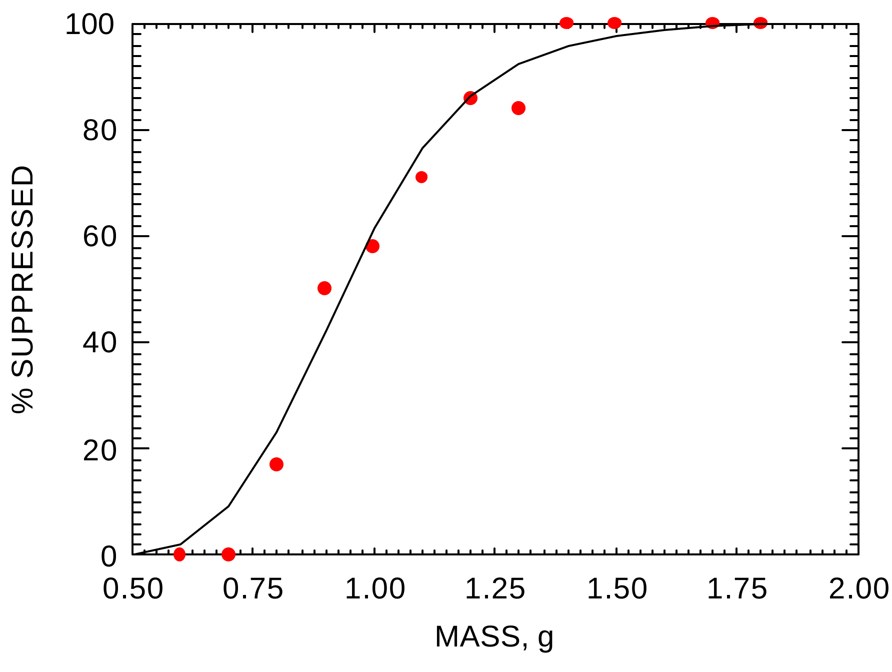


Figure 23. Percent of flames extinguished as a function of mass delivered to flame by SPGG.

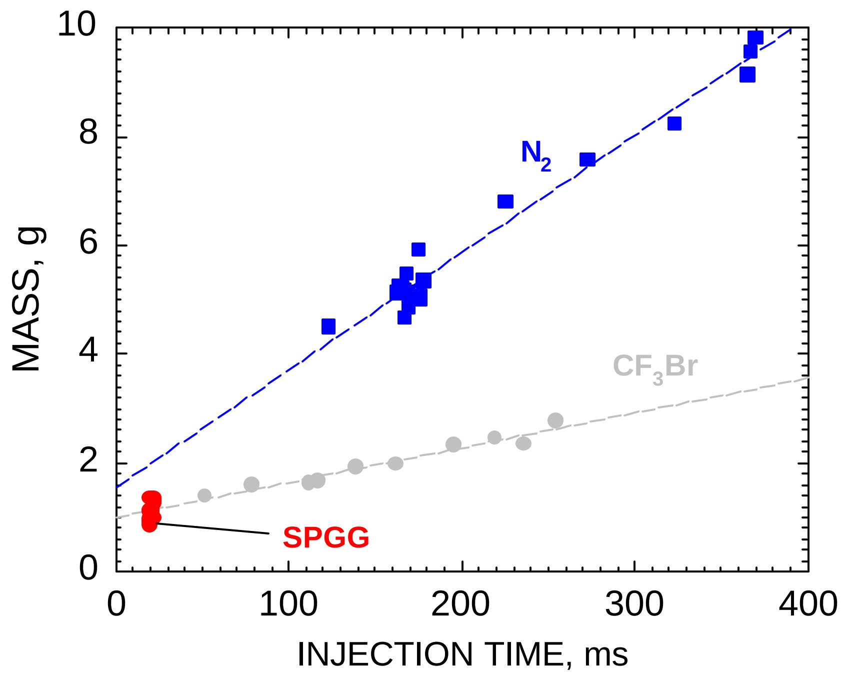


Figure 24. Impact of injection time interval on the mass of agent (CF_3Br, N_2, or SPGG) required to suppress step-stabilized propane pool fire.

Effect of Hot Surface

Figure 2 shows the location of the inverted-vee obstacle placed downstream of the propane pool. An ethane-fueled torch was used to preheat the upstream surface of the obstacle to produce temperatures in excess of 1000 °C as measured by a type-S thermocouple mounted on the exterior face. Pyrometer readings of the interior (i.e., fire-side) surface indicated temperatures were about 50 °C cooler. Experiments were conducted to determine the minimum temperature needed to ignite the propane pool when the air and propane were set to the low flow conditions. Ignition occurred when the hot surface reached temperatures close to 1000 °C.

A spray nozzle was located upstream of the stabilizing step that allowed liquid JP-8 to be sprayed over the propane pool and onto the heated inverted-vee surface. The fuel acted to cool the surface approximately 150 °C below the temperature that had been obtained when only the gaseous propane fuel was flowing. The JP-8 was ignited and formed a flame that stabilized behind the vee when the temperature of the surface exceeded 900 °C.

The procedure used to test for re-ignition of the propane fire was as follows. The propane fire was initiated under the operating conditions of an air flow velocity of 1.5 m/s and a propane flow rate of 33 mL/s, and the obstruction was heated to the temperature desired. The flame was observed to extend past the obstruction. The agent was introduced to the system for three different injection times of 75 ms, 100 ms, and 150 ms, and the occurrence of flame suppression was observed. The cylinder pressure was increased if suppression did not occur, and then the process repeated. The agents tested were nitrogen, HFC125, and CF_3Br. The agent injection time was varied to observed the effect on re-ignition of the propane fuel. The JP-8 stream was then directed against the heated obstruction while the unignited propane still was flowing into the wind tunnel passage. If re-ignition did not occur after 10 s, then the propane flow was terminated. Experiments were repeated with and without the JP-8 stream in order to determine the efficacy of the stream in the re-ignition process. A variety of re-ignition results were observed which depended on the injection time interval of the agent and JP-8 stream. Re-ignition was found to occur when the obstruction was above 900 ^oC (bright red), and a function of the cooling effect by the agent and JP-8 liquid stream.

The influence of the surface temperature was found to be bi-modal: when the temperature of the hot surface (with the JP-8 and propane flowing) was below about 880 $^oC \pm 10\ ^oC$, the amount of agent necessary for suppression was the same as when the surface was unheated; and when the temperature was above 890 $^oC \pm 10\ ^oC$, reignition always occurred within about 10 s independent of higher temperatures or the amount of N_2 added. A similar finding resulted when nitrogen was replaced by CF_3Br, although the measured dividing temperature was about 50 ^oC higher. This difference may have been associated with a build-up of carbon on the hot surface that insulated the fire-side surface from the ethane torch, making an accurate determination of the surface temperature more difficult.

A few experiments were conducted with the temperature reduced to the Leidenfrost point (290 ^oC for JP-8) to determine if an increase in contact time would compensate for the lower temperature. Ignition of the JP-8 and propane did not occur. Satcunanathan and Zaczek [27] measured the ignition delay of kerosene and Diesel fuels on a hot metal surface and found that ignition could occur in less than one second for a 2 mm diameter droplet, but that the ignition time increased for temperatures between about 500 ^oC and 550 ^oC due to surface boiling. No ignition of the JP-8 droplets was observed in the TARPF when the vee-surface temperatures was maintained in the range between 360 ^oC and 440 ^oC. However, Jomaas et al. [14] found that ignition of a JP-8 pool fire would occur in their step-stabilized burner for temperatures in the same range. (See Appendix B.)

Data Correlation

The effectiveness of the gaseous agents is compared to that of the SPGG through use of a simple agent mixing model to describe the suppression phenomena. A more detailed description of the model can be found in Grosshandler et al. [28] and Hamins et al. [9]. A characteristic time, τ, for mixing of the agent into the flame zone can be defined in terms of the air and agent volume flows, $(V'_{air} + V'_{agent})$, and the step height, h, as

$$\tau = \gamma h / \{(V'_{air} + V'_{agent})/[(L-h)L]\} \tag{20}$$

where L is the width of the tunnel and γ is an empirical non-dimensional parameter that relates the ratio of the distance that a fluid element travels within the recirculation zone to the obstacle height. Takahashi et al. [10] measured the characteristic mixing time in a similar facility and found γ to be around 40. Evaluating Eq. (20) for the range of flows and baffle heights examined in the current study and using a value of 40 for γ, τ is found to vary between 0.04 s and 0.40 s.

Hamins et al. [9] found that for a specified injection duration it is possible to relate the mole fraction of agent required to achieve extinction, C, to the characteristic mixing time, τ, according to the following relation:

$$C/C^* = [1-\exp(-Dt/\tau)]^{-1} \tag{21}$$

where C^* can be found experimentally by flowing agent continuously into the air stream at increasing rates until extinction occurs. If the air flow is low enough, the value of C^* is expected to be similar to the cup burner extinction requirements [9]. For propane in a cup burner, Trees et al. [5] found the value of X^* to be 0.32 for N_2, 0.41 for Ar, and 0.039 for CF_3Br. Others have found similar results [29]. Figure 26 compares the suppression results for N_2, CF_3Br, and SPGG through use of Eq. (21), where the normalized mole fraction is plotted as a function of the non-dimensional injection interval. For the SPGG results, C^* is assumed to equal the C^* value for argon. While the data do not fall exactly on the model, the trend of the results are well represented by the single curve when one considers run-to-run variations due to the statistics associated with suppression of a turbulent flame. The results show that the

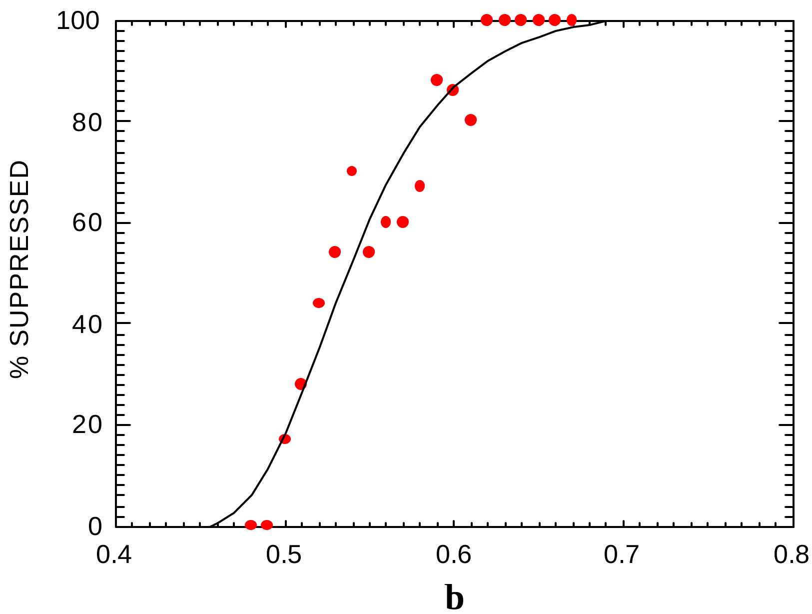


Figure 25. Percent of flames extinguished as a function of the estimated mass fraction of agent.

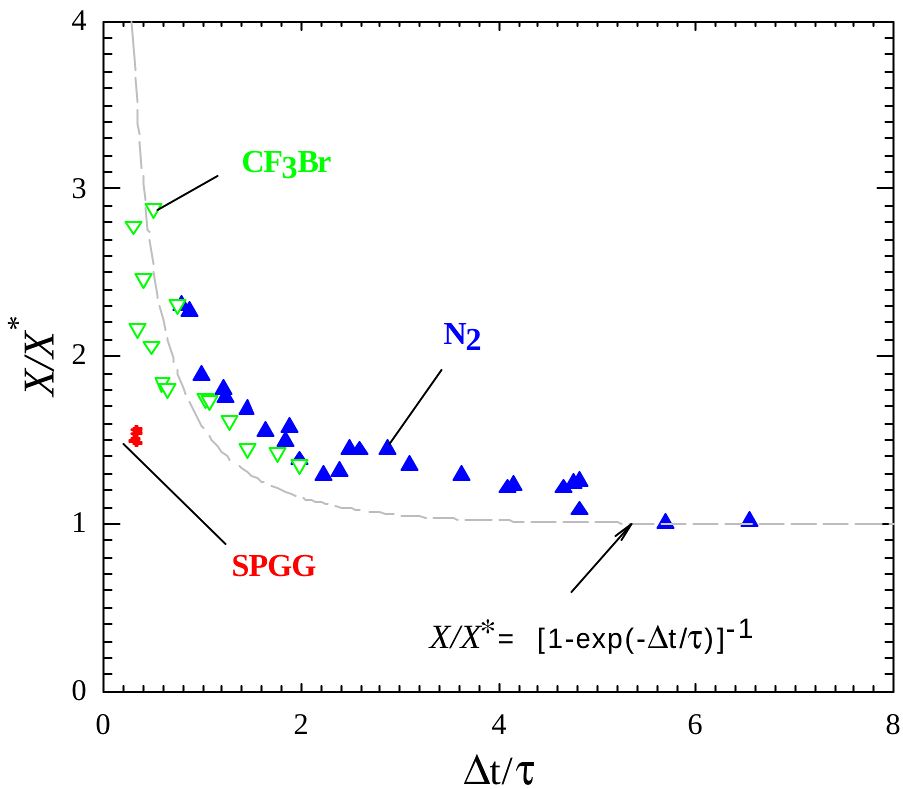


Figure 26. Normalized mole fraction as a function of non-dimensional injection interval, comparing N_2, CF_3Br, and SPGG

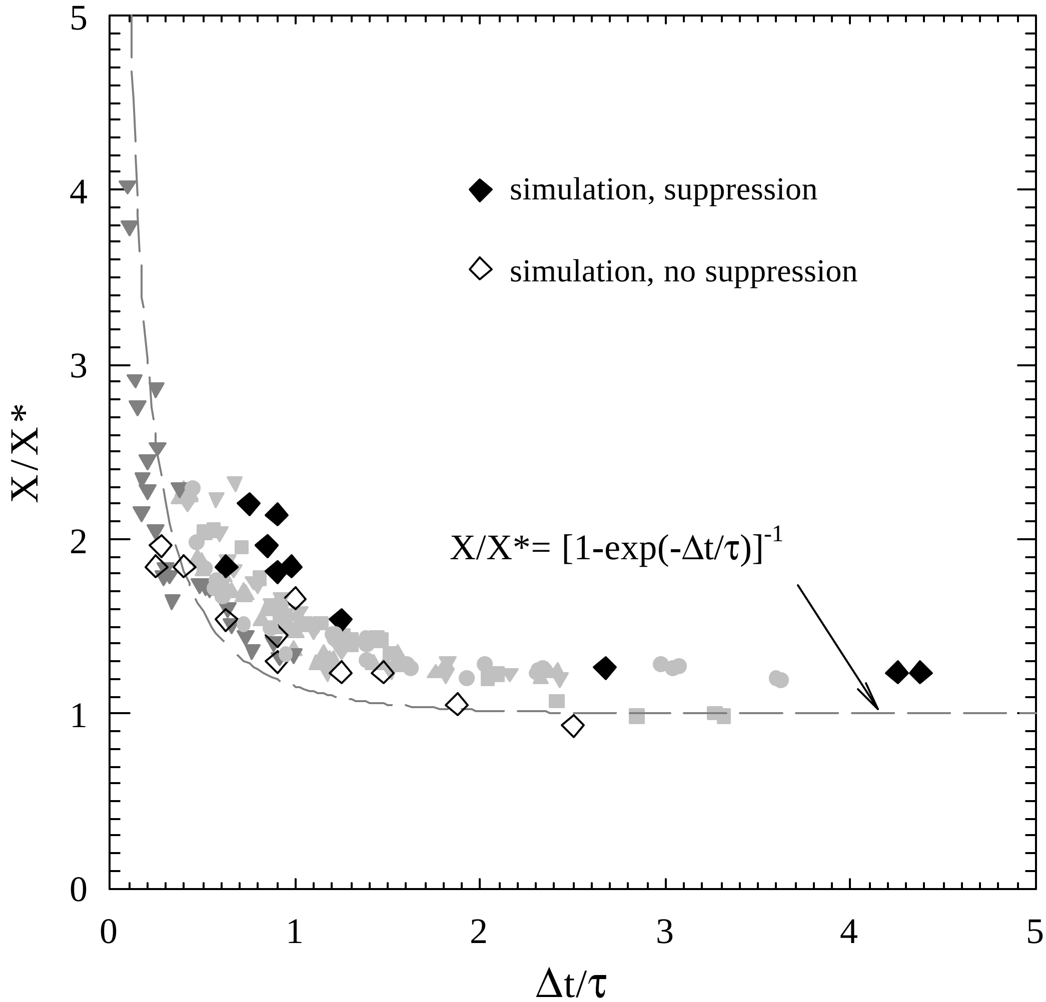


Figure 27. Suppression mole fraction of agent (N_2 or CF_3Br) normalized by cup burner values (X^*) as function of injection time interval normalized by characteristic residence time (τ). Gray symbols: experimental results keyed to Fig. 19; black diamonds: direct numerical simulations with N_2.

effectiveness of the SPGG hybrid significantly exceeds the model predictions.

For laminar diffusion flames strained at intermediate rates, Trees et al. [5] showed that the minimum extinction mole fraction of agent in a counterflow flame decreases from the cup burner value when the strain rate is 50 s^{-1} to much smaller values for a strain rate of 400 s^{-1}. Although the flow in the recirculating region behind a step is much more complicated than in a counterflow flame, the strain rate in the current study should scale with $1/\tau$. When the flow of air is increased sufficiently, the flame becomes strained to the point that agent is not needed for extinguishment (i.e., $C^* \rightarrow 0$) and the flame blows out. In other words, as the air flow in the TARPF increases, the model represented by Eq. (21) in Fig. 26 must be adjusted not only for changes in τ, but also for changes in the value of C^*.

A number of direct numerical simulations of N_2 suppressing the step-stabilized flame were conducted assuming a finite reaction rate with one step chemistry. The injection interval and mole fraction of nitrogen were varied, and the flame structure was followed through the transient period. Either the flame was extinguished, or it was reestablished following the passage of the N_2 pulse. Figure 27 summarizes the results. Open diamonds indicate that no suppression occurred; solid diamonds imply that suppression was successful. The gray symbols refer to the experimental N_2 and CF_3Br data for all geometries examined. The dotted line is Eq. (21).

The computations are able to distinguish regimes of extinction and non-extinction in the case of nitrogen as an agent. The numerical model cannot at present predict what will happen when a chemically active agent like CF_3Br is introduced into the flame. The cooling and dilution of the flame by the agent can be predicted, and hopefully, simplified combustion mechanisms for various chemically-active agents can be developed that will lead to a better understanding of the dynamics of fire suppression.

CONCLUSIONS AND RECOMMENDATIONS

A transient application, recirculating pool fire (TARPF) facility has been built for screening the suppression effectiveness of halon 1301 replacements. The ability to measure the relative effectiveness of alternative agents is key to the development of new fire suppression systems. The physical and chemical properties, and the manner of storage and release of the next generation suppression systems may be quite unlike CF_3Br, but their effectiveness must still be bench-marked against it. The TARPF facility provides the means to screen gaseous agents and solid propellant gas generator concepts in the laboratory for applications in protected spaces involving baffle-stabilized pool fires.

This report represents a comprehensive study, utilizing experimentation, advanced numerical modeling, and analysis to develop and characterize a well-controlled fire suppression facility. Sample experimental results are shown that demonstrate the utility of the facility. Detailed fabrication drawings of the facility are provided in the Appendix of this report. In addition, the experimental procedures are described in detail in the text. Nominal air velocities between 2 m/s and 23 m/s flowing over a backward-facing step were examined. Because the air is metered with a sonic orifice, the injection of agent does not modulate the air flow. The minimum amount of agent for flame extinguishment is substantially and directly affected by the air velocity and the interval of injection. A simple mixing model is useful to explain the observed trend of decreasing suppressant mole fraction with increasing injection duration. A detailed numerical model of the suppression of baffle stabilized fires was developed. The model was successful in simulating the suppression event including a quantitative determination of agent mass requirements.

The facility provides the capability to test solid-propellant gas generators allowing direct comparison of compressed and solid-propellant generated gases for the first time. The capability to test SPGGs under well-controlled laboratory conditions allows evaluation among different propellant formulations, particulate yields, and burning rates for various SPGG designs. Results showed that the effectiveness of the hybrid SPGG exceeded that of CF_3Br and that its effectiveness was significantly greater than expected from the model prediction. Further research could lead to significant improvement of the SPGG as well as traditional agent through enhanced suppressant system design.

Several other research areas require further investigation. These include the effect of the air flow on the steady-state extinction mole fraction of agent, the relationship between agent injection and its concentration history at the flame, and especially the observed differences in the normalized mole fractions of CF_3Br, N_2, and the SPGG for very short injection time intervals.

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