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HYDROGEN DETONATION AND DETONATION TRANSITION DATA FROM THE HIGH-TEMPERATURE COMBUSTION FACILITY¹

G. Ciccarelli, J. L. Boccio, T. Ginsberg, C. Finfrock, L. Gerlach,
H. Tagawa², and A. Malliakos³

Brookhaven National Laboratory
Department of Advanced Technology
Upton, N.Y. 11973

ABSTRACT

The BNL High-Temperature Combustion Facility (HTCF) is an experimental research tool capable of investigating the effects of initial thermodynamic state on the high-speed combustion characteristic of reactive gas mixtures. The overall experimental program has been designed to provide data to help characterize the influence of elevated gas-mixture temperature (and pressure) on the inherent sensitivity of hydrogen-air-steam mixtures to undergo detonation, on the potential for flames accelerating in these mixtures to transition into detonations, on the effects of gas venting on the flame-accelerating process, on the phenomena of initiation of detonations in these mixtures by jets of hot reactant products, and on the capability of detonations within a confined space to transmit into another, larger confined space. This paper presents results obtained from the completion of two of the overall test series that was designed to characterize high-speed combustion phenomena in initially high-temperature gas mixtures. These two test series are the intrinsic detonability test series and the deflagration-to-detonation (DDT) test series. A brief description of the facility is provided below.

1 INTRODUCTION

The concern over the possibility of a combustion event occurring in a water-cooled nuclear reactor during a severe accident was heightened following the Three-Mile Island Unit 2 (TMI-2) accident. After consideration of the pressure pulse induced during the TMI-2 accident, combustion research focusing on hydrogen-air mixtures was intensified. Due to

¹This work was performed under the auspices of the U. S. Nuclear Regulatory Commission and the Japanese Nuclear Power Engineering Corporation.

²Visiting Research Engineer, Nuclear Power Engineering Corporation, Tokyo, Japan.

³Program Manager, U. S. Nuclear Regulatory Commission, Washington, DC.

the high dynamic pressures associated with the detonation mode of combustion, one of the main goals of the research was to determine the necessary geometric and thermodynamic conditions required for detonation initiation. This knowledge is essential in order to help predict the possibility of such an event during a postulated severe accident and to estimate the associated loading on containment.

Under most severe accident scenarios, a containment atmosphere consisting of hydrogen, air, and steam at initial temperatures up to 373K and pressures up to roughly three atmospheres can prevail. For this reason, most of the detonation research recently conducted were at these conditions (Tieszen et al., 1987). Calculations by Yang (1992) have shown that under certain accident scenarios, local compartment temperatures in excess of 373K can occur. Since relevant data at such temperatures is limited and confidence in the modeling of detonations is not high, the need arose to perform further investigations into high-temperature, high-speed combustion phenomena.

The High-Temperature Hydrogen Combustion Research Program at Brookhaven National Laboratory is jointly funded by the U.S. Nuclear Regulatory Commission and the Japanese Nuclear Power Engineering Corporation, sponsored by the Ministry of International Trade and Industry (MITI). The overall goal is to extend the capability to assess potential detonation-type loads in containment during severe accidents, characterized by initial high-temperature and large steam fraction hydrogen-air-steam mixtures. This paper presents the results from two elements of the High-Temperature Combustion Program, dealing with inherent detonability and fast-flame transition.

1.1 Objectives

The BNL High-Temperature Combustion Facility (HTCF) was constructed to investigate hydrogen combustion phenomena in gaseous mixtures of hydrogen-air and steam at temperatures up to 700K. The major component of the facility is a 27.3-cm inner-diameter, 21.3-m long heated detonation tube. The Small-Scale Development Apparatus (SSDA) was constructed to support the design of the HTCF and to augment the experimental data base. A detailed description of the SSDA can be found in NUREG/CR-6213.

The objectives of this phase of the overall experimental program are:

- (1) Provide experimental data on the detonation cell size of hydrogen-air and steam mixtures as a function of initial mixture temperature, in order to determine the effect of temperature in the range of 300K to 650K on the sensitivity of the mixtures to undergo a detonation.
- (2) Evaluate the ability of the ZND physical model to predict the effect of temperature on the detonation cell size of mixtures of hydrogen-air and steam and to compare the measured detonation velocity with the predictions from the classical theory.

- (3) Determine the effect of initial temperature and steam dilution on flame acceleration and deflagration-to-detonation transition phenomena and evaluate the effects of temperature on flame-acceleration limits.

The purpose for acquiring these data and for performing these evaluations has been to enhance our knowledge base in estimating the likelihood of mixtures, prototypical to nuclear power plant severe accident conditions, to undergo a detonation or a high-speed combustion event.

2 EXPERIMENTAL DETAILS

2.1 Experimental Apparatus

The central feature of this facility is the large detonation vessel (LDV), which is a 27-cm diameter, 21.3-m long cylindrically cast, stainless-steel detonation tube, constructed in seven modular, ASME-certified, flanged, 3.05-m long sections. A photograph of the assembled vessels, which were fabricated by Fluitron, Inc., is shown in Figure 1. Four other test sections have been constructed, which can be individually attached to sections of the LDV, to investigate the effects of gas venting on flame acceleration and DDT phenomenon. The Maximum Allowable Working Pressure of the LDV is 10 MPa (100 atm). Each section of the vessel can be independently heated up to 700K, using ceramic heating blankets that surround each modular section of the LDV. Various combinations of hydrogen-air-steam test mixtures, with initial temperatures and pressures respectively ranging between 300K to 700K and 100 KPa to 300 KPa, can be quickly injected into the heated detonation tube. Additional gases, such as nitrogen, carbon dioxide and monoxide, and oxygen, can also be introduced as components of the test mixture. Ignition of the test mixture can be generated in one of several ways: directly by a high-energy spark discharge, by glow-plug igniters, and indirectly by the transmission of blast waves, from an oxy-acetylene gas driver, into the test gas mixture. Accommodations for using high-explosive (HE) discharges for detonation initiation were factored into the design of the LDV, but the use of blast waves, generated by the rapid combustion of a highly sensitive oxy-acetylene mixture (in lieu of a HE discharge), proved successful. Instrumentation and a data acquisition system permit the measurements of initial/final gas composition, dynamic pressure and temperature, flame velocity, detonation wave speed, and detonation cell width.

Some of the systems unique to this facility are described in the appendix. Further details can be found in Ciccarelli (1996).

2.2 Experimental Procedures

The following is a brief description of the steps taken to execute a detonation experiment at elevated initial temperature. Before the vessel heating system is started, a smoked foil is prepared and inserted into the back end of the vessel, after which the heating system is turned on at the remote control unit. The temperature set points for the vessel and other trace heaters are then entered into the computers in the control room. Since the driver is

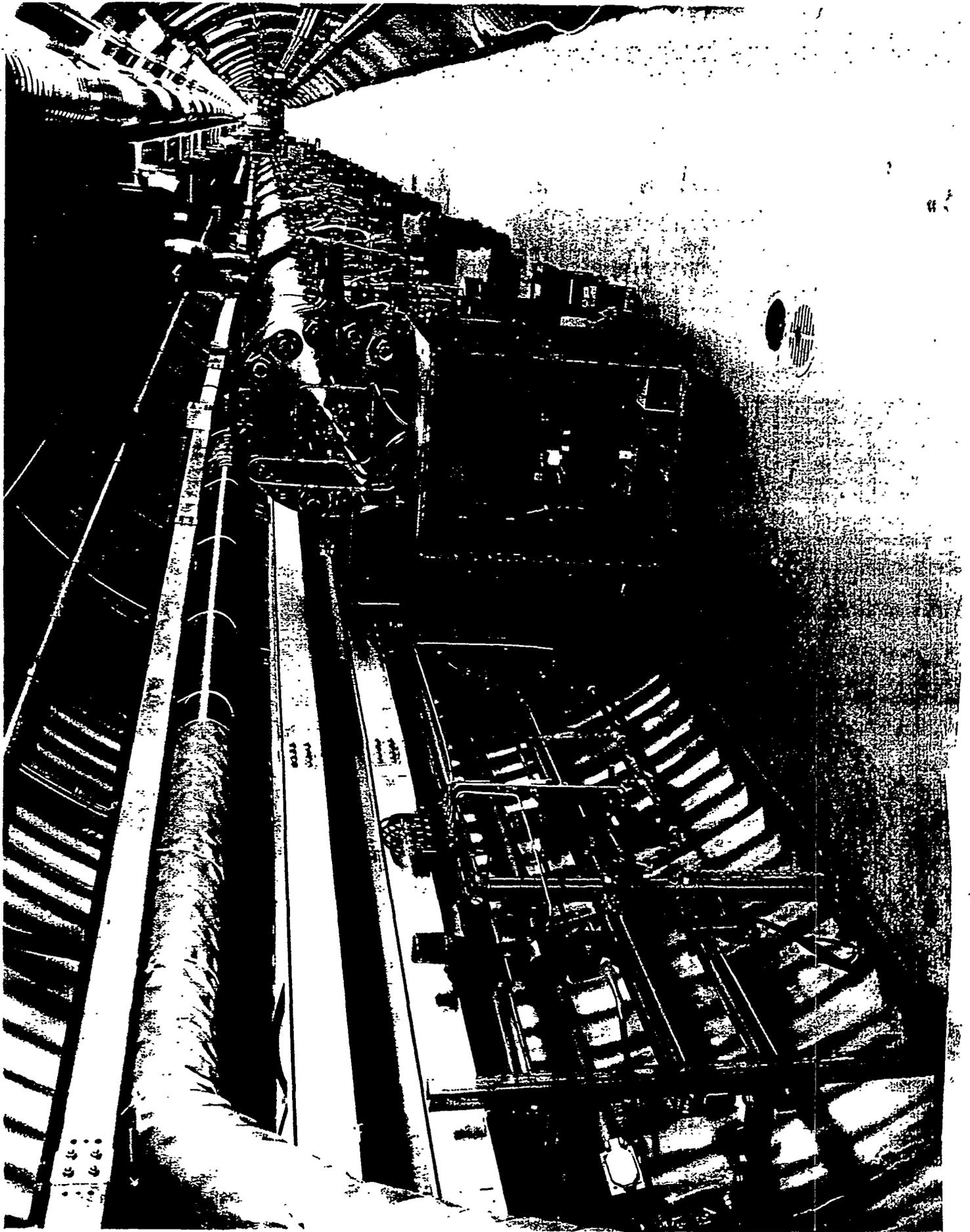


Figure 1: Photograph showing the driver-end of the test vessel inside the tunnel

not heated, the exploding wire used to initiate the detonation in the driver gas can be put into place at any time during the vessel heatup. After the wire is in place, the vessel vacuum can be started. When all the temperature set points have been achieved, all personnel are cleared from the area. The final step is the closure of a large plug door, which satisfies the facility's interlock system that permits the flow of combustible gases (i.e., releases instrument air to the valves) and the charging of the trigger system high-voltage capacitor.

With combustible gas flow enabled, the respective gas constituent flow settings and the various chart and log parameters are input at the computer terminal in the control room. The high-voltage capacitor for the triggering device is charged and the scopes are armed. The operator then starts a program which takes control of the gas filling and firing sequence. The first operation performed by the program is to start the flow of the constituent gases. Before injection into the vessel is initiated, the mixture flow bypasses the test vessel out the exhaust stack, until steady-state flow conditions are achieved. This bypass phase takes 20 seconds, after which the gas is directed into the vessel. The vessel is filled to a pressure just below the prescribed test pressure. After the test gas has been loaded: three test gas samples are taken, the sample bottles valved out, and the driver gas is injected raising the vessel pressure to the test pressure (e.g., one atmosphere). Note, the larger the driver partial pressure, the longer the driver slug is. Once the driver gas is injected, there is a 2-second delay, allowing the valves to close, and the exploding wire is triggered and the detonation is initiated. The combustion products in the vessel are then flushed out through a 7-m high exhaust stack using two 100-HP blowers located at each end of the test vessel. Only after purging has been completed are personnel allowed by the interlock system to enter the tunnel to remove the smoked foil and perform other duties in preparation for the next test.

Tests on flame acceleration and DDT are conducted in a similar fashion, except for this test series, a glow plug is used for ignition in lieu of the gaseous driver. Also to induce turbulence in the flow, equally spaced orifice plates having an inner diameter of 21 cm are installed in the vessel every 27 cm.

3 EXPERIMENTAL RESULTS

3.1 Gas Driver Characterization

One of the unique features of the HTCF is the use of a "diaphragmless" gas driver (i.e., no physical boundary between driver and test gas) to initiate detonations in the test gas. However, the driver gas slug is not as well defined as could be by a diaphragm separating the test gas from the driver gas. As the driver gas is injected into the test vessel, it mixes with preloaded test gas. The degree of mixing and the extent of driver gas convection down the vessel has to be determined in order to be able to calibrate driver conditions and assess driver performance.

3.1.1: Gas Driver Composition

A series of calibration tests were performed to determine the driver gas composition before injection into the vessel and the driver gas distribution inside the test vessel just after injection.

In the first set of tests, the vessel was evacuated, filled with a 20 percent (based on oxygen/acetylene delivery pressures) driver gas mixture to a vessel pressure of 0.05 MPa absolute, and then detonated. The measured detonation velocity down the length of the vessel was 2100 ± 9 m/s. Using the chemical equilibrium code STANJAN (Reynolds, 1986), the CJ (Chapman-Jouguet) detonation velocity for a 20 percent acetylene mixture was calculated to be 2160 m/s, which is only 3 percent higher than the measured velocity. This provided assurances on the calibration of the driver gas composition settings.

The driver gas distribution was measured in the next series by taking gas samples at various axial locations one second after driver gas was injected into an equimolar test gas mixture. Based on the amount of hydrogen detected in a sample, the fraction of the sample consisting of driver gas can be inferred.

The measured axial distribution of the driver gas is given in Figure 2, where the ratio of the driver gas volume to the total gas volume (i.e., driver plus test gas) is plotted versus axial distance from the driver section endplate. Note that the driver gas constitutes between 30 and 40 percent of the gas at the exploding wire location, i.e., the endplate. The driver fraction then drops off asymptotically with distance. From these tests, it appears that the effective driver length scales with the driver volume, or partial pressure.

To some extent, dilution of the acetylene-oxygen driver gas with test gas is advantageous since the detonation pressure in the driver gas will match more closely the detonation pressure in the test gas.

3.1.2 Effect of Driver Length on Detonation Transmission

Another series of experiments was performed in which the driver gas partial pressure, and thus the effective driver length, was varied, and the detonation velocity measured down the length of vessel to ascertain under what driver conditions are stable detonations achieved. The results from these experiments are illustrated in Figure 3. The theoretical CJ detonation velocity and pressure for this rather insensitive test gas is 1233 m/s and 0.377 MPa, respectively. As depicted in this figure, the detonation is initiated immediately in the driver (25 percent oxyacetylene mixture) where the propagation velocity is of the order of 2200 m/s. The detonation velocity quickly decays to a velocity just under the test gas CJ velocity. This figure shows that there is a clear correlation between the distance where the detonation falls off and the effective length of the driver gas depicted in Figure 2. The average terminal velocity for the different driver pressures is similar except for the largest driver (e.g., 1.0 psi), where the average velocity is somewhat higher. For a driver partial pressure of less than 0.2 psi, a detonation was not initiated in the test gas.

Driver Gas Distribution at the Time of Ignition (25% C₂H₂-75% O₂)

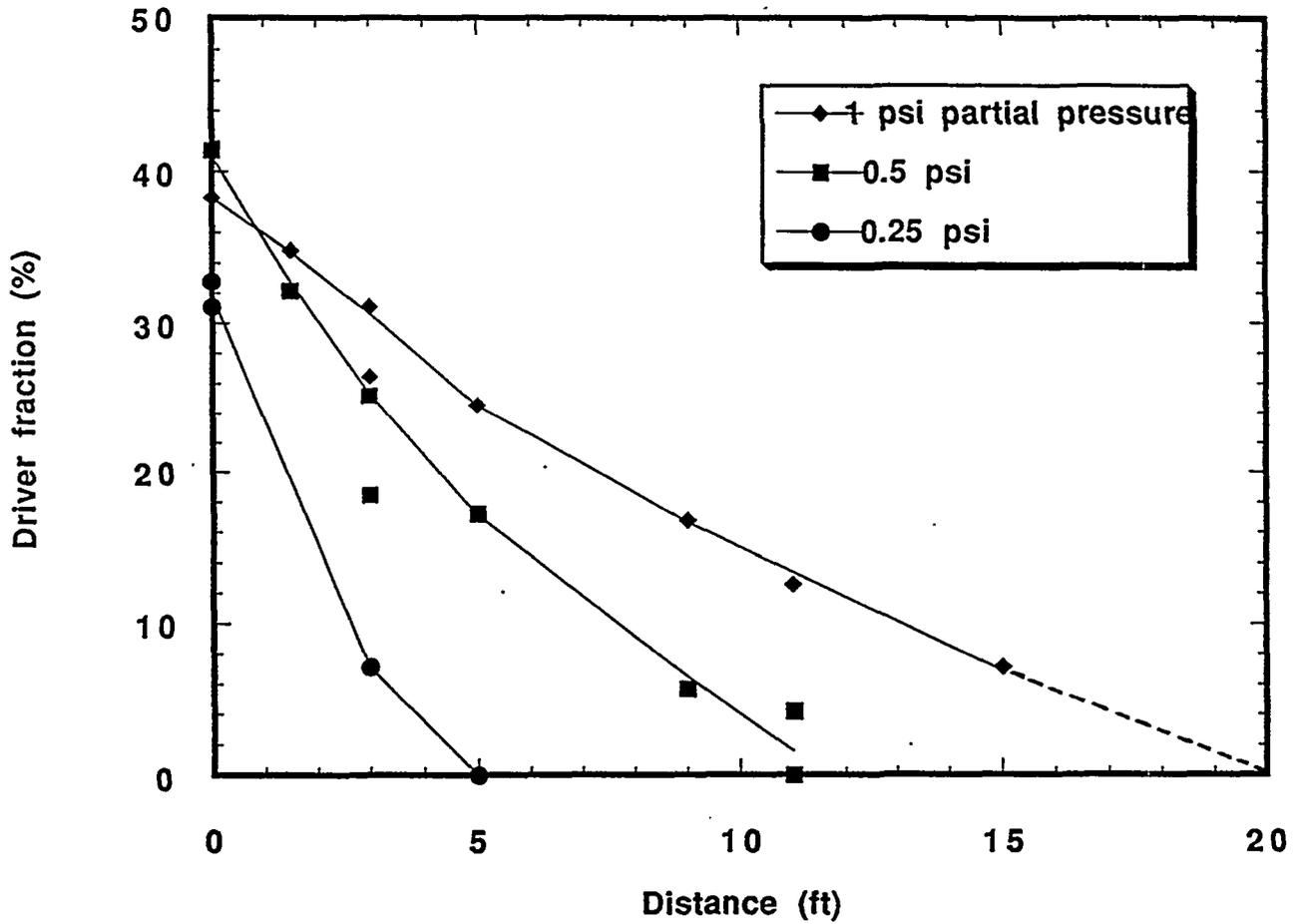


Figure 2: Experimentally measured driver-gas (C₂H₂ + O₂) axial distribution in the test vessel at 1 second after driver-gas injection

Effect of driver length on detonation of 8% Hydrogen-air
at 650K (25% C₂H₂-O₂ driver)

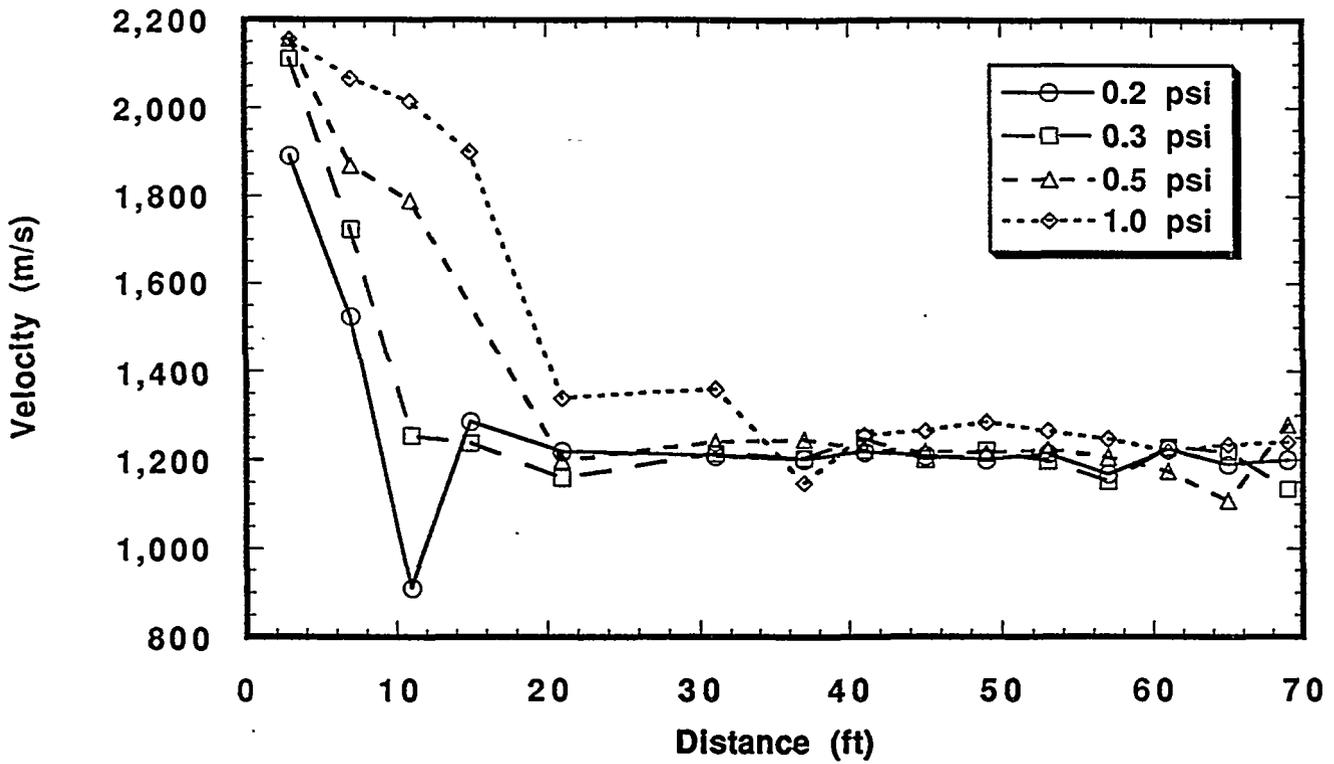


Figure 3: Effect of driver partial pressure (or length) on detonation transmission in an 8 percent hydrogen and 92 percent air mixture at 650K and 0.1 MPa

These experimental findings indicated that the optimum driver conditions for subsequently generating self-sustained detonations in the test gas and for obtaining reliable cell size data are a 0.25-psi driver with a composition of 25 percent acetylene and 75 percent oxygen.

3.2 Detonation Cell Size Measurements

Detonation cell size measurements from smoked foils are presented for hydrogen-air-steam mixtures over a range of initial temperatures and pressures. The cell size data reported are only for detonations that have generated more than three cells across the foil. For detonations generating less than three cells, it is possible that the detonation cellular structure is being influenced by the vessel confinement.

A code, developed by Shepherd (1986), based on the 1-dimensional ZND model of detonation, was used to calculate the thermodynamic structure of the reaction zone and the extent of the fast reactions in these mixtures. The input required by the ZND code is the initial mixture composition and thermodynamic conditions along with the mixture CJ detonation velocity, which is obtained from the equilibrium code STANJAN (Reynolds, 1986). For these tests, the reaction zone length is defined as the distance between the shock wave and the calculated point downstream where the temperature gradient is maximum (i.e., location of maximum energy release rate). The experimentally measured cell size is compared to the predicted cell size derived from the calculated ZND detonation reaction zone length, Δ . The predicted cell size is taken to be proportional to the reaction zone length (i.e., $\lambda = A\Delta$). Other studies have used different definitions for the parameter Δ .

3.2.1 Baseline Experiment at 300K and 0.1 MPa

Figure 4 presents the experimental cell size data from the HTCF as a function of the hydrogen mole fraction, between 15 and 55 percent. Also included in the figure are experimental data from the SSDA (Cicarelli et al., 1994) and from Sandia's HDT (Tieszen et al., 1987). The plot of cell size versus hydrogen mole fraction results in the classical "U"-shaped curve where the minimum corresponds to the stoichiometric composition. The error bars on some of the SSDA results indicate the standard deviation in the cell size measurements from the smoked foil. The ZND model prediction of cell size, using a proportionality constant of 51 for all the mixtures, is shown as a solid line. The scaling factor was chosen by anchoring the SSDA experimental cell size data to the ZND model prediction at the stoichiometric composition (i.e., 30 percent hydrogen). The apparent agreement between the experimental and the model predictions is deceiving because of the logarithmic scale. Measurements show that the scaling factor is strongly dependent on mixture composition, especially for weaker (below 20 percent hydrogen) mixtures. Further details on the lack of a universal proportionality "constant," A , are given in Ciccarelli et al. (1996).

Detonation cell size for hydrogen-air at 300K and 0.1 MPa

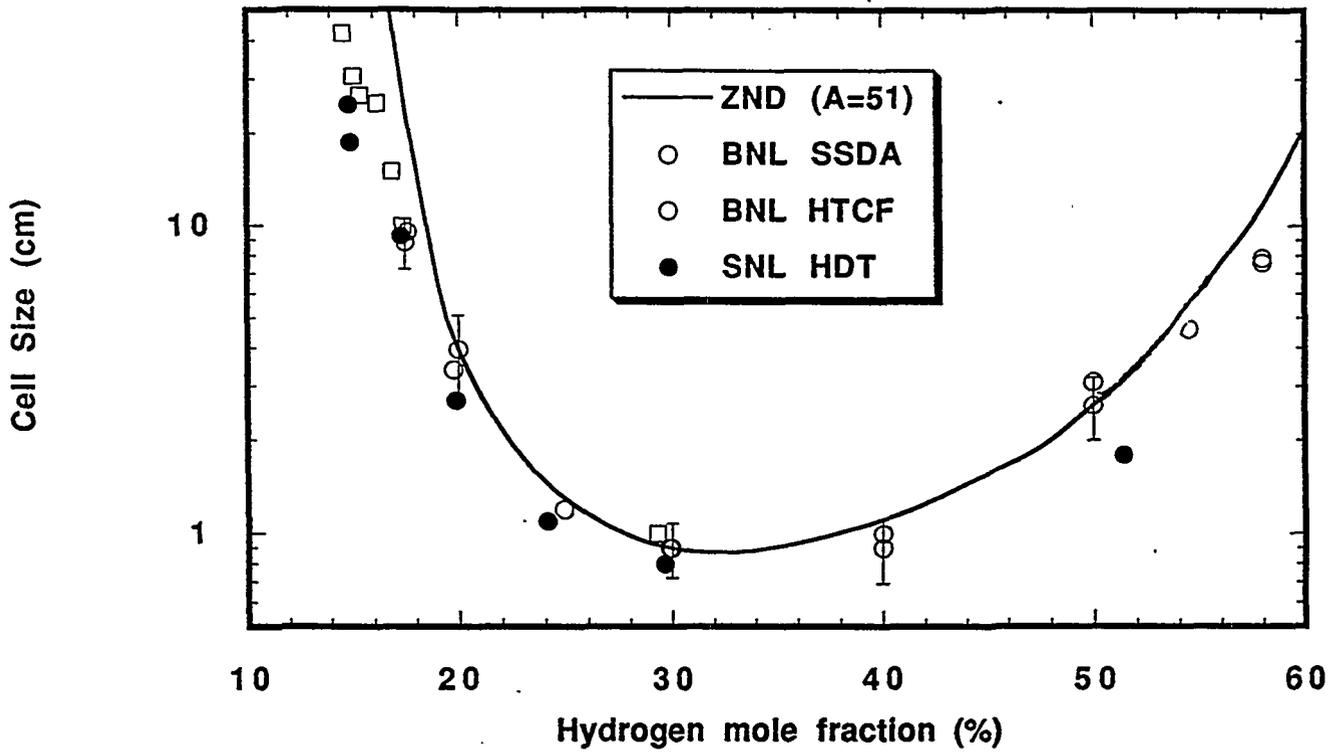


Figure 4: Detonation cell size for hydrogen-air mixtures at 300K and 0.1 MPa

3.2.2 Effect of Initial Mixture Temperature on Cell Size

The effect of temperature on cell size is illustrated in Figure 5, where the 300K data and the 650K data are superimposed. The general trend in the data (i.e., U-shaped curve) at both temperatures is about the same; the only difference is that the 650K curve is much broader than the 300K curve. This plot clearly shows that for a given hydrogen-air mixture, increasing the initial mixture temperature decreases the detonation cell size, especially for lean mixtures. For example, for a 15 percent hydrogen-air mixture, the cell size at 300K is 18.7 cm; and at 650K, the cell size is roughly an order of magnitude smaller (e.g., 1.6 cm). For a 30 percent hydrogen mixture, the effect of raising the temperature from 300K to 650K is to halve the cell size. The other important observation is that increasing the temperature has the effect of widening the detonability limit, i.e., lowering the lean detonability limit.

3.2.3 Effect of Steam Dilution on Cell Size

SSDA data on the effects of steam dilution were extended in the HTCF where sensitive hydrogen-air mixtures could be tested with higher steam dilutions. The HTCF data in conjunction with the SSDA data are shown in Figure 6. The data indicates that for a given mixture temperature, increasing the steam dilution increases the cell size and thus decreases the mixture sensitivity. However, as the mixture temperature is increased, the mitigating effect of steam addition is diminished. At 400K, for example, the maximum mixture steam content that could be tested is 20 percent; and at 650K, mixtures containing up to 40 percent steam resulted in detonations. The experimental data show reasonably good agreement with ZND model predictions with $A = 51$.

3.3 Deflagration-to-Detonation Transition

Extensive investigations in tubes have shown that the transition from a fast flame to a detonation can occur when the flame accelerates to a velocity equal to the sound speed in the combustion products. If DDT does not occur and the flame propagates at the speed of sound of the products (i.e., product flow is choked relative to flame), the propagation mode is referred to as the "choking" regime. To generate fast flames in a finite length tube, arrays of orifice plates are placed down the length of the tube to promote turbulence in the reactants and thereby enhance the burning process. For the stable propagation of a detonation wave down an obstacle-laden tube, Peraldi et. al. (1986) showed that the free flow diameter must at least accommodate one cell width ($d/\lambda \leq 1$). One of the objectives of this phase of the overall test program was to investigate the effects of initial temperature on the flame acceleration process within the detonation tube.

Flame acceleration and detonation transition tests were conducted in the HTCF at temperatures of: 300K, 400K, 500K, and 650K for lean to stoichiometric hydrogen/air mixtures. Selected tests were also performed with mixtures containing 10 percent and 25 percent steam. Parameters measured allowed for the choking and quasi-detonation limits to be determined as a function of mixture composition and initial temperature. Flame velocities, peak overpressures, and DDT run-up distances were also measured.

Detonation cell size for hydrogen-air at 1 atm

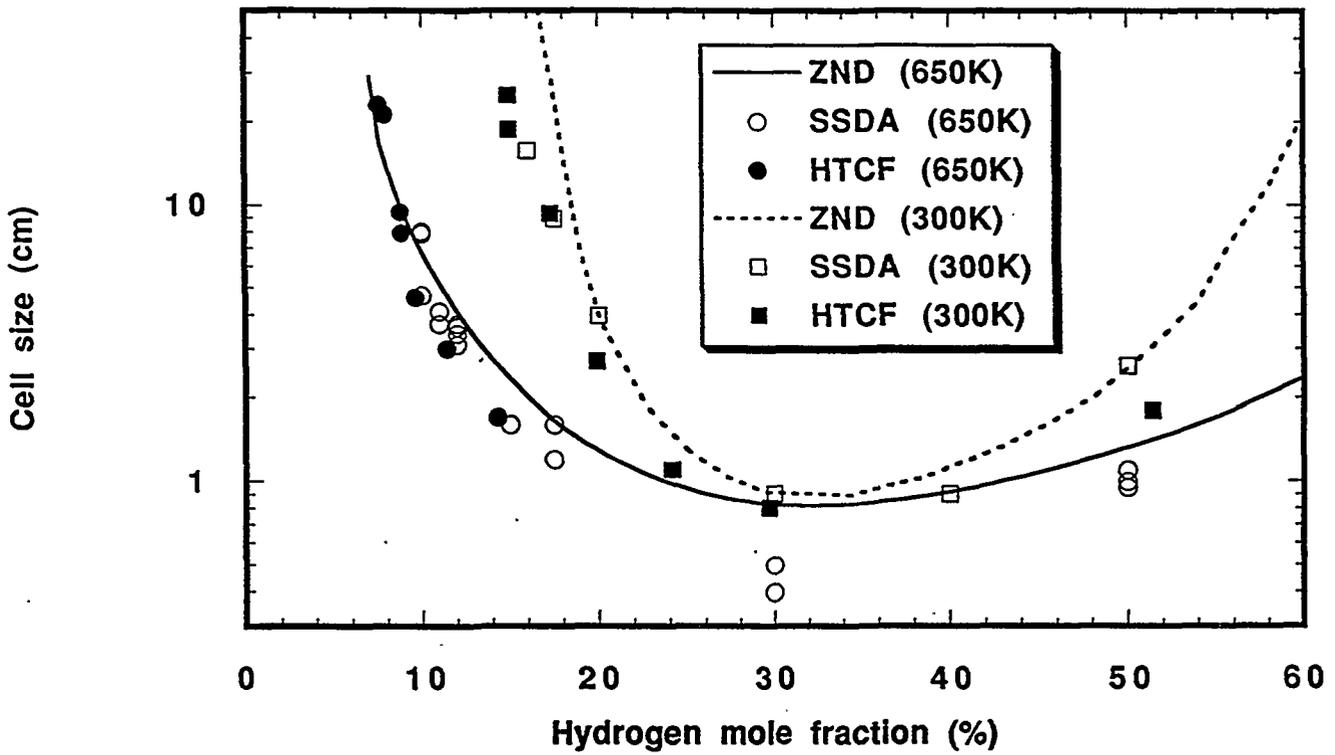


Figure 5: Comparison of detonation cell size for hydrogen-air mixtures at 300K and 650K at 0.1 MPa

Stoichiometric hydrogen-air and steam at 1 atm
 (symbols: SSSA-open, HTCF-closed, HDT-half, lines: ZND A=51)

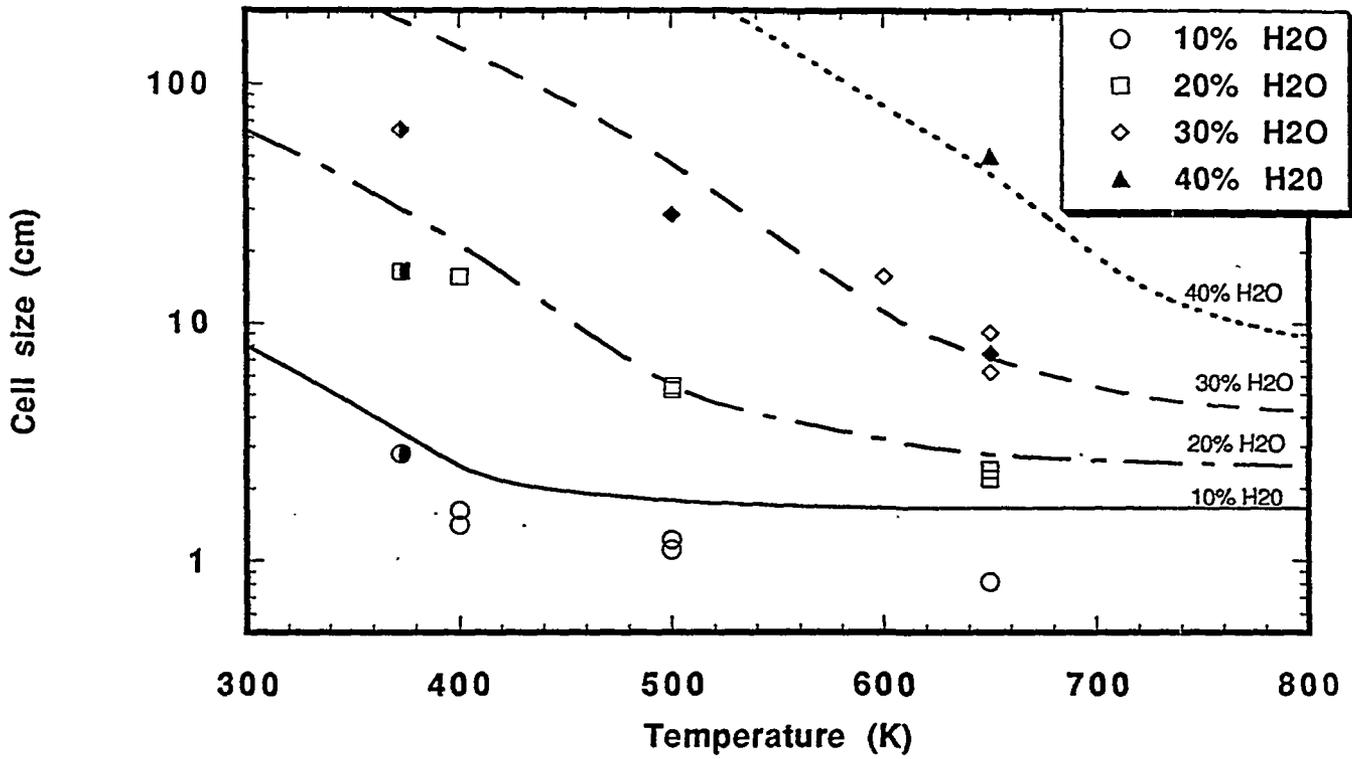


Figure 6: Detonation cell size as a function of temperature for stoichiometric hydrogen-air and steam mixtures at 0.1 MPa

Table 1 summarizes the results of temperature and steam fraction on the two flame acceleration limits. These data were obtained by conducting a series of tests where flame velocities were measured for a prescribed initial temperature and composition. Figures 7 and 8 typify the trends in measured flame velocity versus gas composition for tests conducted at 300K and 650K, respectively. Also indicated are the gas compositions where the flame speed is just above the isobaric sound speed of the combustion products and the calculated CJ detonation velocities. Figure 9 presents similar data for tests conducted at 400K and 10 percent steam.

Further details on this phase of the High-Temperature, High-Speed Combustion Program can be found in Ciccarelli et. al. (1996).

4 SUMMARY AND CONCLUSIONS

For any hydrogen-air-steam mixture, cell size measurements have shown that increasing the initial mixture temperature in the range of 300K to 650K while maintaining the initial pressure of 0.1 MPa decreases the cell size and thus makes the mixture more sensitive. In the HTCF, the effect of steam dilution on cell size was tested in stoichiometric and off-stoichiometric (e.g., 18 percent hydrogen) hydrogen-air mixtures. Increasing the steam dilution (or partial pressure) in hydrogen-air mixtures at 0.1 MPa initial pressure increases the cell size and thus decreases the mixture sensitivity, irrespective of initial temperature. It was also observed that the desensitizing effect of steam on hydrogen-air detonability diminished with increased initial temperature. The maximum steam dilution resulting in a detonation was 50 percent steam in a stoichiometric hydrogen-air mixture at 650K and 0.1 MPa. Although not shown in this paper, a limited number of experiments were carried out to investigate the influence of initial mixture pressure on detonation cell size. There was very little effect observed in the pressure range tested, 0.1 MPa to 0.24 MPa, for relatively weak hydrogen-air-steam mixtures. It can be shown that the minimal sensitivity to pressure is also predicted by the ZND model.

A 1-dimensional, steady-state ZND model, with full chemical kinetics, has been used to predict cell size for hydrogen-air-steam mixtures at different initial conditions. The cell size is taken to be proportional to the calculated ZND reaction zone length ($\lambda = A \Delta$). Taking A to be a constant, the ZND model did a relatively good job at predicting the overall trends in the cell size data as a function of mixture composition and initial conditions. However, a comprehensive comparison of the theoretical predictions with the experimentally measured cell size has demonstrated that the two are not linked by a simple constant of proportionality, A . In this investigation, it has been shown that A is also a function of the initial mixture temperature, such that $\lambda = A(\phi, T_0)\Delta$.

Evaluations of the flame propagation regimes for these conditions and for the HTCF also indicate that cell size alone does not dictate the DDT limit.

TABLE 1

Flame Acceleration Limits for Hydrogen-Air Mixtures Without Venting

Temp (K)	Choking Limit	DDT Limits	
	% H ₂	% H ₂	d/λ
300	11	15	1.0
500	8	12	1.5
650	11	11	5.5

Flame Acceleration Limits for Hydrogen-Air-Steam Mixtures Without Venting

Temp (K)	% Steam	Choking Limit	DDT Limits	
		% H ₂	% H ₂	d/λ
400	10	12	18	0.7
500	25	14	24	1.5
650	25	16	19	0.8

DDT experiments with hydrogen-air at 300K and 1 atm

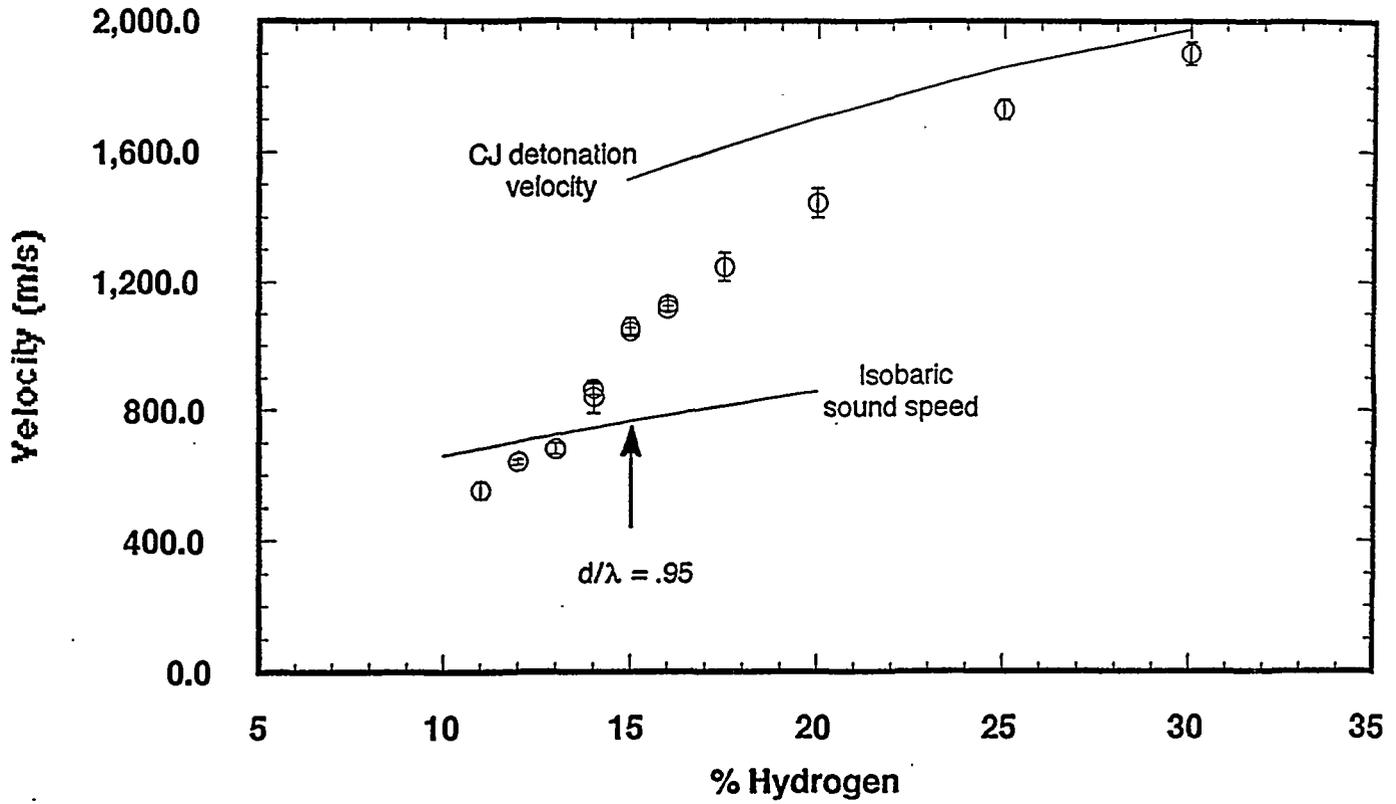


Figure 7: Measured flame velocity vs. gas composition for tests conducted at 300K

DDT tests with hydrogen-air at 650K and 1 atm

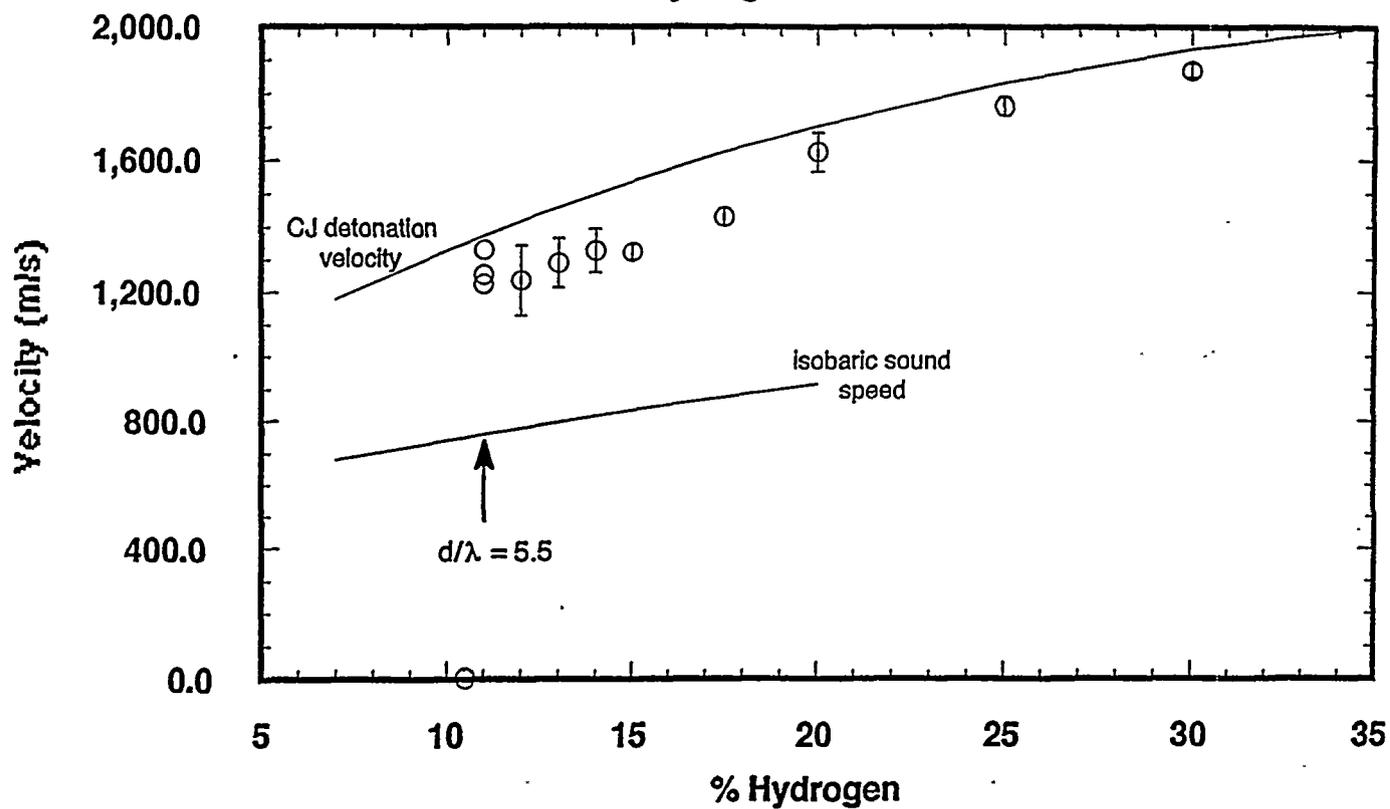


Figure 8: Measured flame velocity vs. gas composition for tests conducted at 650K

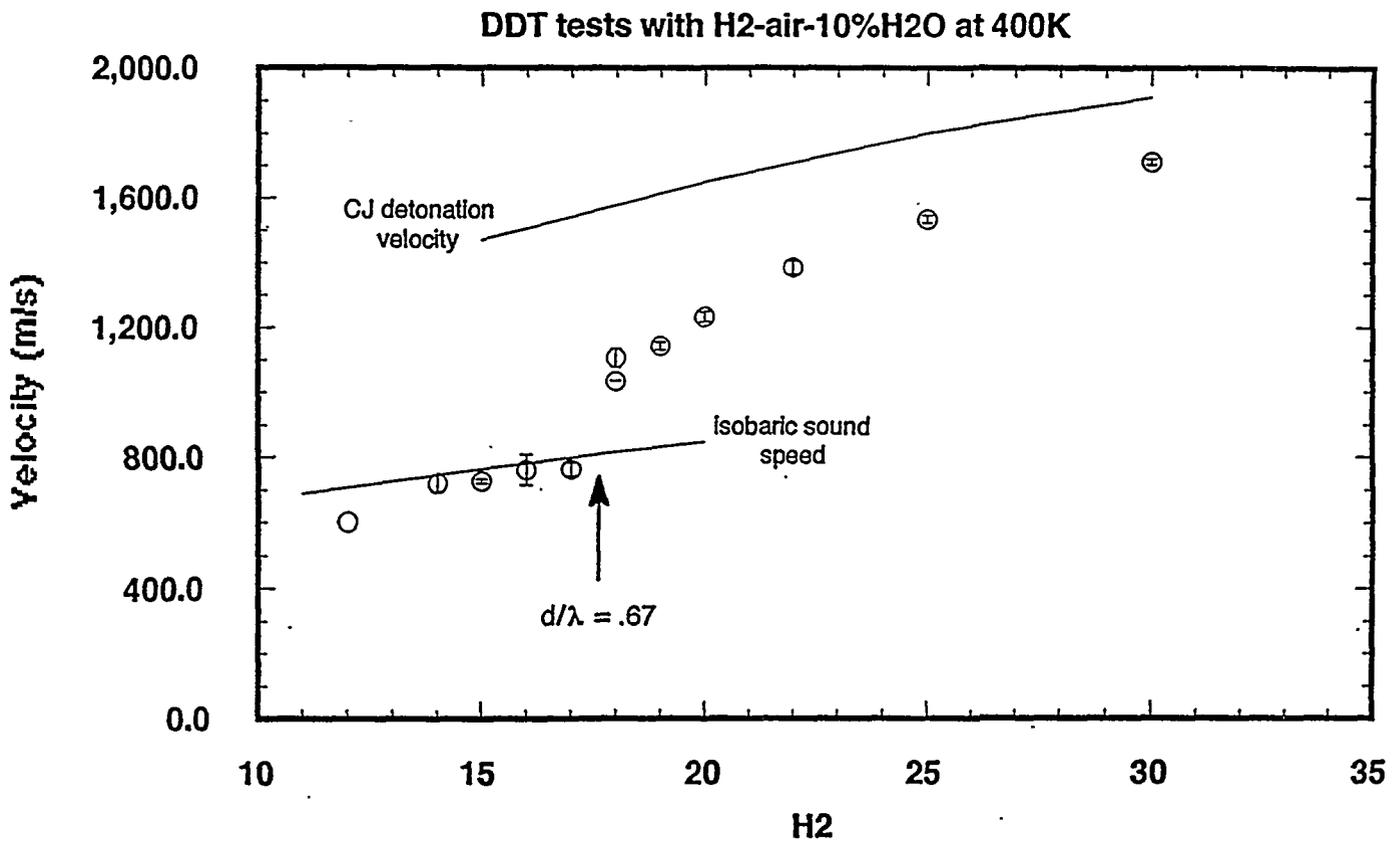


Figure 9: Measured flame velocity vs. gas composition for tests conducted at 400K and 10 percent steam

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APPENDIX

SALIENT FEATURES OF THE HTCF

The High-Temperature Combustion Facility (HTCF) was designed and constructed with the objective of studying detonation phenomena in mixtures of hydrogen-air-steam at initially high temperatures. The central element of the HTCF is a 27-cm inner-diameter, 21.3-m long cylindrical test vessel capable of being heated to $700\text{K} \pm 14\text{K}$. A unique feature of the HTCF is the "diaphragmless" acetylene-oxygen gas driver which is used to initiate the detonation in the test gas.

Gas Driver Detonation System

A gas driver system is used to initiate the detonation in the HTCF test vessel. The concept, similar to that used in the SSDA, is to produce a short slug of acetylene-oxygen mixture at one end of the vessel and initiate a detonation in this mixture using an "exploding wire." The detonation from the driver gas slug is then transmitted into the test gas. For tests at elevated temperature, the driver section (i.e., the first 3.05-m long test vessel section) is unheated so that the acetylene-oxygen mixture does not burn upon injection.

The driver gas plumbing and the high-voltage trigger circuit used for the exploding wire can be seen in the foreground in the photograph in Figure 1. The acetylene-oxygen mixture is injected into the vessel via a sparger system consisting of four equally spaced perforated tubes. The driver gas composition can be varied either by the needle valves or by the bottle regulator delivery pressure. The acetylene and oxygen are mixed by flowing the two gases co-axially into a manifold chamber and then into the four sparger tubes, which penetrate 10 cm into the vessel through the endplate. The four tubes enter the vessel at equally spaced radial positions just inside the vessel inner-wall. Each tube is oriented to direct the oxyacetylene gas inwards toward the vessel centerline.

The detonation in the acetylene-oxygen driver is initiated by the shock wave produced by an exploding wire. The exploding wire is a fine copper wire fastened between two electrodes, mounted onto an instrumentation plug that protrudes into the center of test vessel through the driver endplate. The wire is made to explode by passing a large current through it, derived by shorting a 20-microfarad, 7.5-KV capacitor.

Heating System

The heating system was designed, manufactured, and installed by Cooperheat Inc. of Piscataway, New Jersey. The assembled, insulated test vessels are each capable of being heated to the maximum operating temperature of 700K in four hours.

The heating system is segmented into three major components, consisting of the heating elements, the power control unit, and a remote control unit. The remote control unit

houses two multi-zone PID temperature controllers which are adjusted through a computer located in the control room. This control unit is also the terminal for all the control zone thermocouples on the test vessel. The power control unit distributes the power to the various heating zones on the vessel. Each test vessel has a mounted junction box where the power cables enter and are terminated at a power distribution block. The heater element leads hang below the vessel and are connected to the appropriate power distribution block.

The heating elements, which are mounted directly on the vessel, are resistance wires woven into a ceramic pad that are fastened to the vessel using stainless-steel pipe clamps. The heater pads were custom designed to give maximum heater coverage on each test vessel section. The entire vessel is covered with two layers of 2.54-cm thick Kaowool insulation blankets. A typical 3.05-m long vessel pipe section has three heating zones which can be controlled independently, and each flange pair also has its own heating zone yielding a total of 29 heating zones for the entire vessel.

Instrumentation

The instrumentation used in the present experiments are identical to those used in the SSDA (Cicarelli, 1994). Test gas thermodynamic conditions, such as temperature, pressure, and mixture composition, are all monitored and logged before a detonation is initiated. Standard K-type, exposed junction probe thermocouples with an accuracy of 1.2K are used to monitor the gas temperature. The vessel pressure is monitored using a strain gage Wika pressure transducers having an operating range of 0 to 0.34 MPa absolute with an accuracy of 0.1 percent of full scale. The flow rates in the test gas constituents are determined by fixing the upstream pressure in each of the choked Fox venturis. The Fox venturis have a manufacturer's quoted accuracy of 2 percent. Three gas samples are taken from the vessel, using pre-evacuated 150-ml gas cylinders, before each test. After the test, the samples are then analyzed as a further check on hydrogen content using a gas chromatograph (Carle Model 311H). The gas chromatograph is periodically calibrated using hydrogen gas standards with an accuracy of 2 percent. For tests with steam, the venturi mass flow rate is used to back out the steam content. Steam is provided through a 24kW Reimers boiler that can deliver 100 psig, saturated steam at 81 lbm/hr.

Detonation pressure is measured using fast-response PCB 113A24 quartz piezoelectric pressure transducers. Due to the high-temperature environment, the transducers are housed in special water-cooled adaptors. These transducers have a maximum pressure range of 6.8 MPa with a rise time of 1 μ s. The accuracy of the transducer is less than 1 percent of full scale. Time-of-arrival of the flame or detonation front is measured using ionization probes. These probes consist of two electrodes which penetrate about 1.27 cm into the vessel. The electrodes are connected to a simple circuit which outputs a voltage signal when the electrodes are shorted by the passage of the reaction zone. The time-of-arrival is used in conjunction with probe spacing to determine the average detonation or flame velocity. For relatively low-speed flames, the output of thermocouples is also used to estimate the flame velocity.

Detonation cell size is measured using the "smoked-foil" technique. Aluminum foils are used, typically 2-m long, 0.5-mm thick, which when shaped into a cylinder can cover almost the entire vessel inner-wall. The foil ends were riveted to 3-mm thick, 5-cm wide steel rings placed on the inside of the foil for added strength. The inside of the foil is smoked after the rings are mounted. The cylindrically shaped foil is placed upright on one end, and a kerosene lamp is burned inside. The foil is sooted incrementally from the bottom to the top in sections roughly 30-cm high. As discovered from the SSDA tests, for experiments at elevated temperature, the best results were obtained when the foil was first coated with a very thin layer of silicone fluid before smoking.

Data Acquisition and Control

All data acquisition and control equipment is located in the control room. A 486 Gateway PC equipped with several commercially available Strawberry Tree data acquisition and control cards and software are used to run the experiments from the control room. Three ACPC 12-bit analog input cards (16 channels each) are used for monitoring pressure transducer and thermocouple signals. One ACPC digital input/output card (40 channels) is used for actuating valves and monitoring limit switches. One ACAO 12-bit analog output card (6 channels) is used to feed the set points to the three PID pressure regulators. A Personal 488 card is also installed to provide GPIB capabilities to the system. The cards are driven by an icon-based Strawberry Tree program called Workbench.

Two 100-MHZ, 4-channel LeCroy 314L digital oscilloscopes are used to capture the high-speed output signals from the piezoelectric pressure transducers and the ionization probes. Hard copies of the oscilloscope signals were made after each experiment.

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