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Gas Explosion Research With Large Spherical Vessel

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Abstract— **This paper presents explosion severity characteristics of a gas-air-nitrogen mixture measured with a large scale (3.66-m diameter) Spherical Steel Vessel established at CSIR-CBRI. The relatively large size of vessel makes it particularly suitable for ignition, flammability, and detonability studies with minimum wall effects and the data serve as reliable input for designing explosion safety measures and explosion risk assessment for industries. Investigations on explosion characteristics of various gases have been undertaken. Some results for methane-air-nitrogen mixtures are covered as representative explosion data. The explosion pressure and time to reach the same are given as a function of nitrogen dilution. The information can be used to design the explosion safety measures for installations handling this gas.**

Index Terms—**Gas, Spherical vessel, gas air nitrogen**

I. INTRODUCTION

The explosion hazard exists in industries handling combustible gases, vapours and dusts. An accurate knowledge of flammability, detonability and explosion characteristics of these substances is essential for realistic appraisal of fire and explosion hazards in mining and chemical industries; and for efficient prevention of explosions and mitigation of their disastrous effects. Design of explosion protective measures-explosion-resistant construction, explosion relief venting, automatic isolation of interconnected spaces and explosion suppression, etc.-requires explosion severity data- maximum explosion pressure and rate of pressure rise (Bartknecht, 1981). There exists large amount of experimental data on limit of flammability and detonability and explosion characteristics for many combustible gases and vapours which are usually determined in laboratory-scale apparatus and their evaluation is strongly affected by experimental conditions. The results reported by different workers are not in agreement. For example, for some gas-air mixtures reported lower limit concentrations are: 5 to 6.3 % for methane and 2.72 to 3.45 % for ethylene; and upper limit values are: 12.8 to 15 % for methane and 13.7 to 34.0 % for ethylene (Linnett and Simpson, 1961). Such variations are due largely to vessel size effects.

For solving these problems, European researchers developed several larger spherical test chambers for explosion studies. A 1 m^3 Vessel designed by Bartknecht (1981) became standard in Europe for measuring gas/dust explosion violence data and was accepted worldwide (ISO, 1985). Continuous efforts to minimize size of vessel to ease tests resulted in acceptance of a 20-L Sphere designed by Siwek as minimum internationally accepted size of laboratory apparatus providing a level of control over significant experimental variables and resolved many uncertainties and contradictions of the past data giving explosion characteristics comparable to 1m^3 Vessel (Swiek,1985). CSIR-CBRI has also established 20-L Spherical Vessel similar to Siwek Sphere for studying explosion parameters of industrial gases, vapours and dusts (Mittal,2011). These sizes are suitable for many combustion studies, but they are less adequate for conducting limit-of-flammability experiments or basic studies on the growth and propagation of explosion in which the vessel walls influence the flame propagation. The limits of detonability of gaseous mixtures are influenced similarly by vessel diameter. Application of small scale data to large scale plant units also requires information on behavior of flammability of materials at large scale.

The course of large expanding flames is of great concern wherever large volumes of flammable gases or vapours are ignited accidently. Buoyant forces are considered responsible for high flame propagation rates. The flame and pressure development data are essential in designing explosion safety measures like explosion venting requirements. Such information is presently needed by the industries for protection against ignition of combustible gas-air-inert systems. Effect of vessel size in propagation of flame front or detonation wave may be explained by thermal considerations as heat loss from flame front to the vessel walls by radiation, convection, and conduction is assumed a controlling factor in flame front propagation. Burning velocities are expected to decrease with decreasing vessel diameter until enough heat is lost to quench the flame; that is, quenching diameter has been reached for the given mixture under prevailing environmental conditions. The large scale vessels are required to determine the maximum flammable range and explosion data of combustible mixtures from the safety point of view.

Accordingly, the CSIR-CBRI has provided a 3.66-m diameter Spherical Vessel - the unique facility fabricated for use in this type of research. The paper presents features of this 3.66- m diameter Spherical Vessel for experimental evaluation of explosion parameters of gases, vapours and dusts necessary for designing explosion protection and mitigation systems and risk assessment of explosive atmosphere. Some experimental results for methane gas are given as an example. There exist explosion data for methane gas from small scale test facilities (Bartknecht,1981; Dahoe and Goey, 2003; Pekalski et al.,2005) and recommended for designing explosion safety measures for industrial units according to various standards (NFPA ,2007,2008) which are based on 20-L or 1 m^3 data. The present research in 3.66-m diameter sphere will provide data on explosion pressure of methane –air mixture and effect of adding nitrogen on explosion pressures based on actual measurements in the large vessel which will serve as a more reliable and scientific input to the design of explosion safety measures.

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II. LARGE SCALE EXPLOSION EQUIPMENT, INTSTRUMENTATION AND EXPERIMENTAL PROCEDURE

Figure 1 shows the experimental test facility -3.66m diameter Spherical Steel Vessel. There are seven access ports for installation of various systems such as vacuum creation, gas or vapour introduction, circulation, ignition, pressure measurement and a door. The large size of the sphere permits personnel to enter and install special instrumentation and equipment for measuring various combustion parameters over comparatively large distances from the initiating source and make possible experiments at elevated, atmospheric and reduced pressures. Three of these access ports are 6´´ diameter nozzles located 90^o apart from each other on the equator of the sphere; the door opening is centered at this level also. In addition, a 6´´ nozzle is located at the bottom and a 12´´ nozzle at the top. The remaining two ports are 1-inch diameter pipes situated in the lower portion of the vessel. To facilitate operations within the sphere, the chamber is equipped with a removable floor of steel grating. The vessel is fabricated of firebox quality steel and is designed for a static pressure of 20 kg/cm^2. This was stress-relieved and subjected to a hydrostatic test (30 kg/cm^2) and a vacuum test (450 micron of mercury) for 30 minutes. Under transient conditions of explosions the vessel may be expected to withstand pressures even greater than 30 kg/cm^2 depending upon the duration of the pressure pulse. As a safe practice, the design pressure is not exceeded during the tests.

The large sphere can be used for many different types of combustion studies, some of which could not be conducted in a smaller vessel. These include: basic and applied research on the flammability and detonability characteristics of combustible-oxidant mixtures under vented and unvented conditions, and at elevated pressures or reduced pressures where ignition energy and vessel size must be sufficiently great to differentiate flammability limits from ignitability limits; studies of propagation of flames or explosions over large distances, thereby yielding a greater amount of information on variables like burning velocity, pressure rise, temperature rise, etc. at large distances from the initiation source with minimum wall effects in comparison to that possible by using smaller spherical vessel; and observations of shape and appearance of flames and their reactions for relatively long duration in various environmental conditions. The vessel is also used for investigations on physical processes associated with propagation of an explosion, e.g., studies of diffusion and stratification of gases to compare flame propagation and extinguishment in uniform and non-uniform combustible mixtures; and examination of effect of venting and induced turbulence to obtain data applicable to some of the environmental conditions encountered in practice. Studies can be carried out for vented and unvented explosions using various sizes of explosion vessels within sphere, mechanism of such explosions and their damage effect on surrounding materials under various degrees of confinement and with different ignition energy sources.

The ignition system installed in the Vessel has two brass electrodes (3 mm diameter) connected to a circuit which produces an electrical spark. The spark generating system has three units: variable capacitor bank having capacitors with different values; variable voltage supply/ continuous spark unit; and step-up transformer. The spark is triggered by high voltage transformer using two-electrode system connected to the secondary winding of the transformer and fitted in the Vessel. The self-inductance of the secondary coil of the trigger transformer is 1 mH. The spacing between the electrodes is 6 mm. The spark may be continuous or of known energy. With variable combination of capacitance and voltage, it is possible to obtain sparks with ignition energies in the range 0.5 mJ – 3.2 J using this circuit. There is precise electronic synchronization between gas circulation and spark onset. Energy discharged from the capacitor is calculated from the following formula, assuming no energy losses in the transformer,

$$W = \frac{1}{2}C(V_i^2 - V_f^2) \quad (1)$$

Where,

W - Discharge energy, J

C - Total capacitance of discharge circuit, F

V_i - Initial voltage of charged capacitor, V

V_f - Final voltage of charged capacitor, V

A spark energy measurement system has been integrated in the spark generation circuit and net spark energies generated for various combinations of capacitance and voltages are determined in the conventional way by measuring current and voltage across spark gap as a function of time and integrating the power-verses-time curve. Measured spark energies were typically 90-95 % of the theoretical energies computed using equation 1.

The sphere was evacuated and predetermined volume of commercial grade methane, air and nitrogen were added. Gas-air-nitrogen mixture was then circulated through a 6´´ diameter sidearm gas circulation system, until gas samples from the top and bottom gave identical fuel concentration within 0.1%, to ensure homogeneous mixtures. Samples of test mixtures were taken prior to ignition and were analyzed by a gas chromatograph. For the present experiments, ignition was done at the centre of the sphere with a 0.6 cm gap continuous spark from the discharge of a 10 kV transformer. Spark duration was held constant, approximately at 0.2 second. Dynamic pressure during explosion was measured using piezoelectric and strain gauge pressure transducers provided at two ports. Pressure-time curve was recorded by storage oscilloscope or high speed chart recorder. The electric pulse generated at the moment of spark firing is used to trigger the digital storage oscilloscope that monitors and stores both the pressure verses time signal and triggering signal. Experiments for explosion violence measurement were conducted over a wide range of gas concentration. Each experiment was repeated thrice.

III. EXPERIMENTAL RESULTS & DISCUSSION

Experiments were carried out for a gas-air mixture having stoichiometric concentration of methane gas in air and for addition of various amounts - 5, 10, 15,20,25,30, 35 or 40 % - of nitrogen to this mixture. The composition of mixtures used for experiments is given in Table 1. All the mixtures were centrally ignited. Figure 2 shows typical explosion pressure verses time curves on reproduction of experimental data obtained in the 3.66-m diameter Spherical Vessel for stoichiometric methane-air mixture and for addition of 5 % nitrogen to this mixture. Experimental explosion pressure curves similar to Figure 2 were recorded for all the mixtures given in Table 1.

These pressure-time records were analysed for determination of maximum explosion pressure, rate of pressure rise and time to reach the maximum explosion pressure. The results are presented in Figure 3. Detailed data will be presented in a separate publication. The pressure-rise and rate of pressure rise in the constant volume deflagration were strongly influenced by the inert concentration of the combustible gas mixture. No explosion could be recorded for 40 % nitrogen addition. The minimum nitrogen required for inerting methane-air mixtures was not determined but it is known to be greater than 35 and less than 40 %. The reported value of critical oxygen concentration is 12 % (Zabetakis, 1965), which indicates that nitrogen addition requirement for stoichiometric methane-air mixture is slightly more than 35%.

Pressure rise was not a simple cubic function of time, although this law was nearly approximated for some mixtures during the early period of burning. Rates of pressure rise were maximum near the end of the combustion period and ranged from high of 40 bar/s for the 9.52 % methane-air mixture to less than 1 bar/s for the mixture with 35 % added nitrogen. The time to reach to maximum explosion pressure for combustion of a stoichiometric methane-air mixture can be estimated by equation 2 (Zabetakis,1965)

$$t = 75.V^{1/3} \qquad (2)$$

Where,
t - Time in milliseconds
V- Volume of spherical vessel in cubic feet.
The predicted time to reach the maximum explosion pressure using equation 2 is 0.72 s which is in close agreement with the experimental value – 0.7 s presented in Fig.ure 3 for stoichiometric methane-air mixture.

IV. CONCLUSION

The explosion severity data - maximum explosion pressure and time to reach the maximum explosion pressure determined with large spherical vessel for methane gas reported in this paper may be used in practical design of various explosion safety measures aimed at suppressing the disastrous effects of explosion e.g. for sizing explosion relief venting systems or inerting. The large size of sphere permits the study of large buoyant flames and minimizes errors - uncertainties due to adiabatic compression of unburned gas involving pressure and corresponding temperature effects, spatial distribution of the flame luminosity for defining flame front location, and temperature gradients across the flame front controlling density of the burnt gas- in determining burning velocities. Only limited data are presented here. Further details will be presented in future publications.

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Table 1. Composition of methane-air-nitrogen mixtures used for experiments

Sl. No.	Nitrogen added, Vol. %	Methane, Vol. %	Air			Total Nitrogen in mixture, Vol. %
			Vol. %	Oxygen Vol. in air	Nitrogen Vol. in air	
1	0	9.52	90.48	19.00	71.48	71.48
2	5	9.04	85.96	18.05	67.91	72.91
3	10	8.57	81.43	17.10	64.33	74.33
4	15	8.09	76.91	16.15	60.76	75.76
5	20	7.62	72.38	15.20	57.18	77.18
6	25	7.14	67.86	14.25	53.61	78.61
7	30	6.66	63.34	13.30	50.04	80.04
8	35	6.19	58.81	12.35	46.46	81.46
9	40	5.71	54.29	11.40	42.89	82.89

Fig.1. Large- 3.66-m diameter Spherical Vessel for explosion research studies

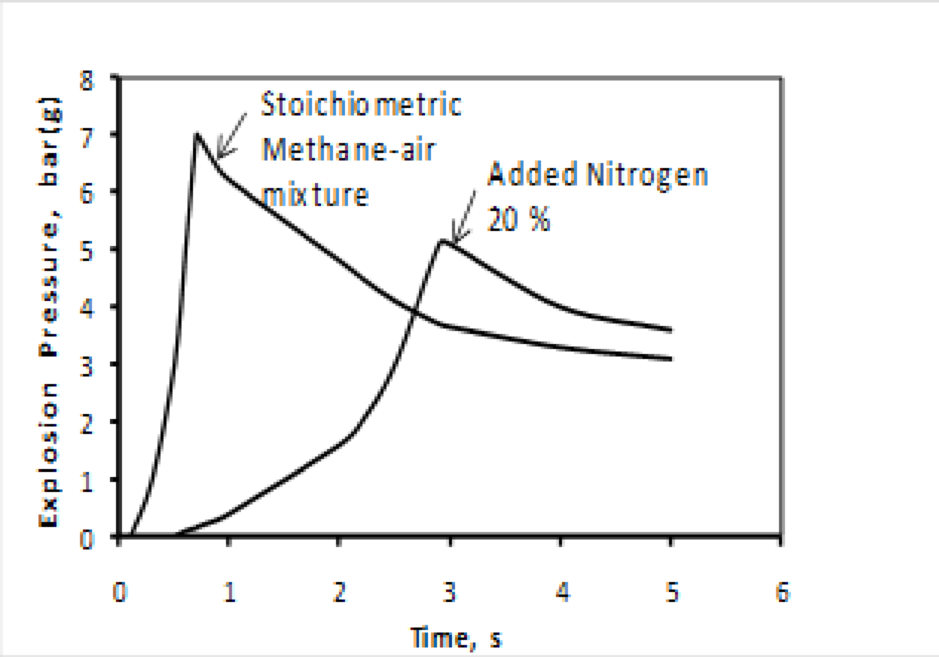

Fig.2. Typical explosion pressure curves for methane-air and methane-air-nitrogen mixtures in 3.66-m diameter Spherical Vessel

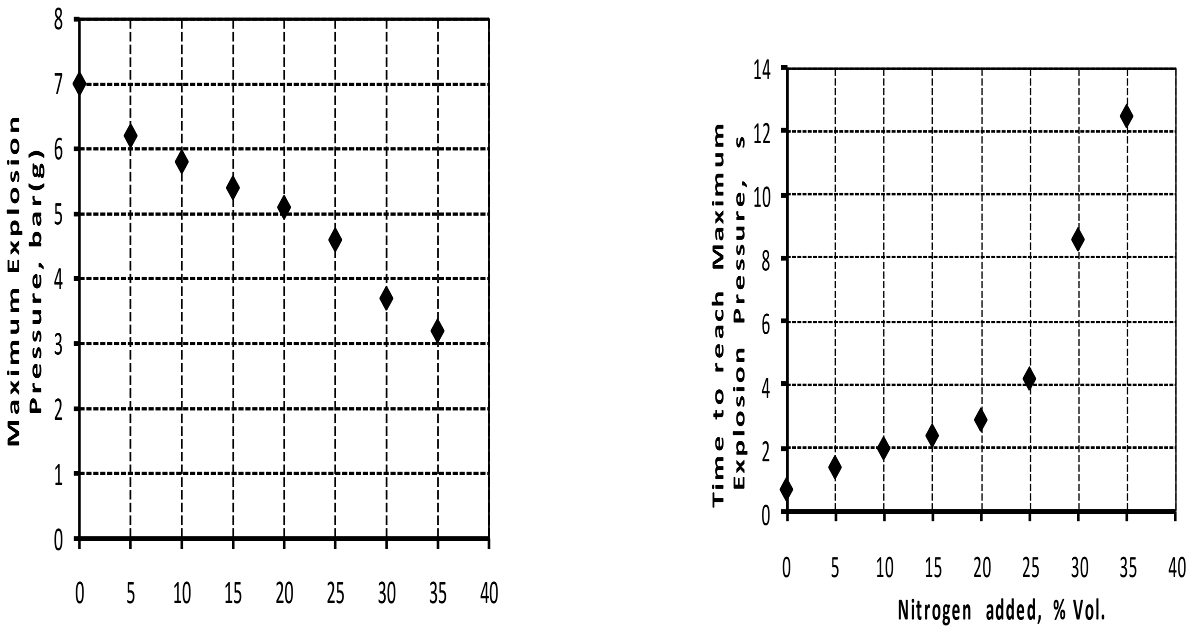

Fig.3. Maximum explosion pressure and time to reach the same for various added nitrogen concentrations to stoichiometric methane-air mixture in 3.66 m diameter Spherical Vessel