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Analysis of Exhaust Gas Behavior for Small Scale Solid Propellant Motors (Static Test) using Gaussian Plume Dispersion

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Abstract:
Static testing of solid motors can affect the environment (human being, flora, and fauna) due to the toxic effects of the exhaust gases, acid rain occurrence. During static test of solid propellant motors, large amounts of exhaust gases containing toxic by-products like Al_2O_3, HCl, CO, etc., are released into the atmosphere. These exhaust gases rise to atmospheric stabilization heights, and then start dispersing and diffusing through air. Upon reading the ground concentration levels of the toxic byproducts will present a risk to humans and also to the environment. This paper brings out the experimental study methodology for measuring the concentration of the exhaust gases namely hydrogen chloride and aluminium oxide particles at various downwind distances from the test bed. Dispersion model helps to validate the theoretical calculations as well as to assess the impact of exhaust gas pollutants. It also helps to take necessary precaution to ensure that minimum adverse effects are caused to the human beings for the future static tests.

Keywords:*Exhaust gas, plume dispersion, static test.*

I. INTRODUCTION

This solid motor is a qualification motor for the ballistic evaluation purpose, which is extensively used for the evaluation of burn rate for all the solid motors such as S139, S200, PSO-XL, and HPS3. The typical small scale solid propellant grain is having 42 kg propellant weight with a grain length of 1000mm and 203 mm OD with 10 lobed star port configuration this motor provides ballistic properties like thrust, pressure, burn time and subsequently burn rate is computed based on the measurement of web thickness. These are the basic parameters for full scale solid rocket motor performance prediction. During static test of small scale solid motors, large amounts of exhaust gases containing toxic by-products like AL2O3, HCl, CO, etc., are released into the atmosphere. These exhaust gases rise to atmospheric stabilization heights, and then start dispersing and diffusing through air. Upon reading the ground concentration levels of the toxic byproducts will present a risk to humans and also to the environment. To estimate the safe corridor (TLV in ppm) dispersion modeling is one of the tools to predict downwind concentration of small scale solid motor static test. Gaussian plume dispersion model uses the mathematical equations and algorithms, which calculate small scale solid motor static test dispersion. The dispersion modeling of any toxic gases and particle requires source model. It describes the release incident, which is based on the estimation of discharge rates, total quantity released (or total release duration) Wind velocity and Wind direction. The amount of exhaust gas that is produced depends on the area of the flame front and engine designers use a variety of hole shapes to control the change in thrust for a particular engine. The hot exhaust gas is passed through a nozzle which accelerates the flow. Thrust is then produced according to Newton's third law of motion. The ammonium per chlorate (AP) particles first decompose in the sub-surface region to form per chloric acid ($HClO_4$), and the HTPB binder decomposes to produce fuel in the form of hydrocarbon fragments and hydrogen. $HClO_4$decomposes further to form smaller

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oxidizing species. These decomposed gases consisting of fuel and oxidizer components mix together to form a diffusion flame above the propellant-burning surface.This small scale 42kg solid motor will burn for 6 seconds with exhaust gas temperature of 3000K. Exhaust gases from burning his propellant will consist of HCl, CO, CO_2, H_2, H_2O, N_2 and Al_2O_3.

Table 1. Constituents of the Exhaust Gases

Gas	HCl	CO	CO_2	H_2	H_2O	N_2	Al_2O_3	Other gases
Weight percentage (%)	20.35	23.75	2.82	2.28	8.42	8.52	33.83	0.03

The dispersion calculations provide an estimate of the area affected and the average vapour concentrations expected. The simplest calculations require an estimate of the release rate of the gas (or the total quantity released), the atmospheric conditions (wind speed, time of day, cloud cover), surface roughness, temperature, pressure and perhaps release diameter. More complicated models may require additional detail on the geometry, discharge mechanism, and other information on the release.

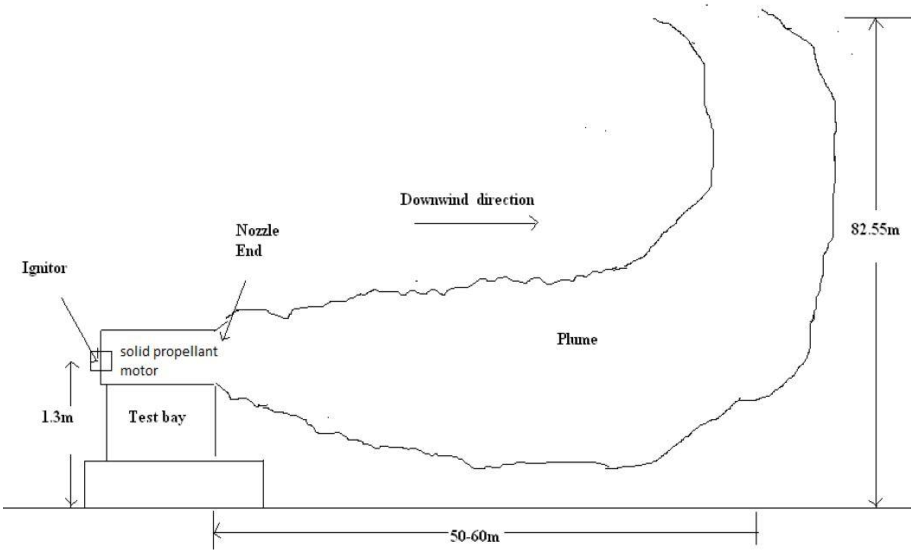

Fig.1. Plume Rise Model

II. LITERATURE REVIEW

The propellant of solid rocket engine is contained in the combustion chamber itself. The propellants burn on exposed surface to produce hot gases which produce a reactive force when expanded through at the time of the rocket nozzle. Most solid rocket propellant contain all the materials necessary for sustaining combustion [1]. Weather conditions release have a major influence on the extent of dispersion. The primary factors are the wind speed and the atmospheric stability. Atmospheric stability is an estimate of the turbulent mixing; stable atmospheric conditions lead to the least amount of mixing and unstable conditions to the most [2]. Dense gases may also be released from a vent stack; such releases exhibit a combination of dense and Gaussian behavior with initial plume rise due to momentum, followed by plume bend over and sinking due to dense gas effects. Far downwind from the release, due to mixing with fresh air, the plume will behave as a neutrally buoyant cloud. Since most releases are in the form of a jet rather than a plume, it is important to assess the effects of initial momentum and air entrainment on the behavior of a jet [3]. Atmospheric diffusion is a random mixing process driven by turbulence in the atmosphere. The concentration at any point downwind of a source is well approximated by a Gaussian concentration profile in both the horizontal and vertical dimensions [4]. The ground-level concentrations of pollutants downwind of a tall chimney decrease as the effective height of the stack increases. The effective height of the stack is the actual height plus the rise of the plume centerline due to momentum and buoyancy of the effluent [5]. Stack Plume Rise is a conceptual phenomenon which is mainly dependent on two forces, namely, Buoyant and Momentum force. Buoyant forces are governed by temperature, heat emission rate of the stack exit gases whereas Momentum forces are governed by Stack exit gas velocity. Plume Rise is also dependent on various factors like Atmospheric wind speed, Atmospheric stability condition, and Atmospheric turbulence besides some other internal parameters like Stack gas temperature, Heat emission rate, Stack Height and Stack gas exit velocity. The Plume Rise is an important parameter in the overall air pollution control mechanism which directly interferes the dispersion of pollutant over a period of time and space, the more is the plume rise, the better would be the dispersion of air pollutants resulting into less ground level concentration of air pollutants [6]. Three main points should be considered for a typical AP/ HTPB composite propellant. First, the mass loading of AP is much higher than that of HTPB. Second, AP monopropellant is highly reactive and can sustain exothermic reactions without the presence of any fuel binder. Third, the size of AP particles plays a decisive role in dictating the burning behavior of the composite propellant [7].

III. METHODOLOGY

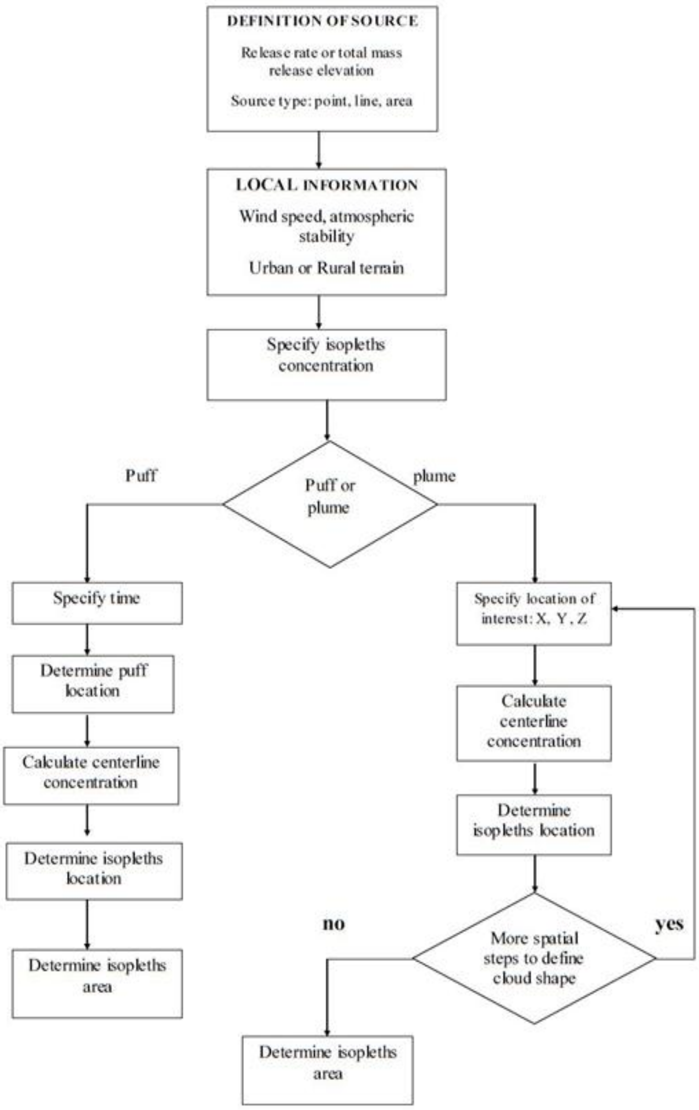

Fig.2. Methodology

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SOLID MOTOR STATIC TEST

The prediction of plume rises and exhaust gas behaviour of any solid rocket propellant firing requires more input data and detailed analysis. In this section an attempt is made to predict the plume rise by using Moses and Carson model. and exhaust gas behaviour by using Gaussian plume Dispersion model. During static tests because of the horizontal let-out, the exhaust gases will be pushed to certain distance horizontally and then the cloud will go up due to thermal buoyancy.

MOSES AND CARSON MODEL

This model is used for predicting the plume rise for solid propellant firing,

Plume rise,

$$H = \left(\frac{2.64}{U}\right) \times Q_h^{0.5}$$

Where.

H = Rise of exhaust gas due to thermal buoyancy in meters

Q_h = Heat emission rate in kJ/sec

U = Wind velocity in m/sec

$Q_h = mC_p (T_e - T_a)$

C_p = Specific heat of exhaust gas (1.825 kJ/kg/K)

m = Emission rate of exhaust in kg/sec (7 kg/sec)

T_e = Exhaust gas temperature (3300 K)

T_a = Ambient temperature (310 K)

CALCULATION OF EXHAUST GAS DISPERSION FROM SMALL SCALE SOLID MOTOR STATIC TEST

Extensive theoretical and experimental studies on dispersion of exhaust gas cloud from static test of S200 and S-125 solid motor have been carried out. However during static tests because of the horizontal let-out , the exhaust gases will be pushed to certain distance horizontally and then the cloud will go up due to thermal buoyancy . Diffusion model of ellipsoidal cloud at stabilization is assumed. Calculation were made with the worst condition of wind towards land on June 22, 2018 with wind velocity (6.25 m/s) which is the approximate wind velocity measured during a static test of Agni motor and also to indicate the pattern of concentration changes with different wind velocities . the method of calculation is given below[1-10].

Table 2. Recommended Equation for passquill-gifford dispersion coefficient for plume dispersion

Pasquill-gifford stability class	σ_y(m)	σ_z(m)
C	0.11*X(1+0.0001*X)^(-1/2)	0.08*X(1+0.0002*X)^(-1/2)
D	0.08*X(1+0.0001*X)^(-1/2)	0.06*X(1+0.0015*X)^(-1/2)

PLUME MODEL

The plume model describes a continuous release of material. The solution depends on the rate of release, the atmospheric conditions, the height of the release above ground, and the distance from the release. In this case the wind is moving at a constant speed, u, in the .x-direction. The equation for the average concentration for this case is,

$$(c)(x,y,z) = \frac{G}{2\pi\sigma_y\sigma_z u} exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \times \left\{exp\left[-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2\right]\right\}$$

Where,

(C) (x ,y ,z) is the average concentration (mass/volume),

G is the continuous release rate (mass/time)

σx, σy, σz are the dispersion coefficients in the x, y, and z directions (length)

u is the wind speed (length/time)

y is the cross-wind direction (length)

z is the distance above the ground (length)

H is the height of the source above ground level plus plume rise (length)

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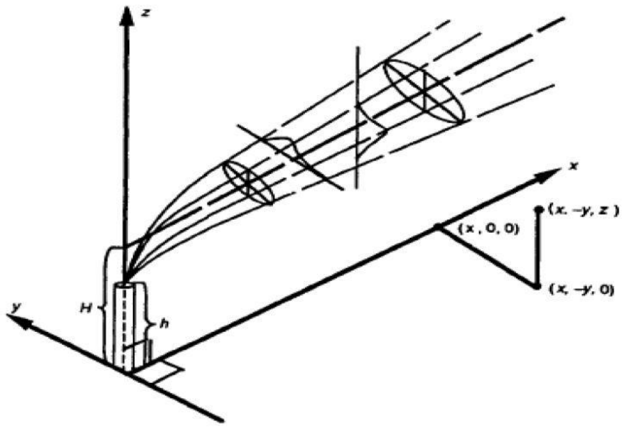

Fig.3. Three-dimensional view of Gaussian dispersion from an elevated continuous Emission source. From Turner (1970)

The typical requirement is to determine the cloud boundary at a fixed concentration [11-13]. These boundaries, or lines, are called isopleths. The locations of these are found by dividing the equation for the centreline concentration, that is, (C)(x,0,0,t), by the general ground level concentration. The resulting equation is solved for y to give,

$$y = \sigma y \sqrt{2ln \frac{(c)(x,0,0,t)(centerline)}{(c)x,y,0,t)(desired)}}$$

IV. RESULTS AND DISCUSSIONS

Based on the scenarios considered the exhaust gas released from the motor is studied using Pasquill-Gifford Stability Classes for atmospheric conditions. The concentration isopleths of various scenarios for different ppm concentration conditions are given below. It is better understood that, the first hand information about the dispersion of Exhaust gases (HCl, CO, Al2O3)in the form of above mentioned quantitative analysis and derivation of safe distance can be used to evacuate the personnel during static test of Small scale solid motor[14-15].

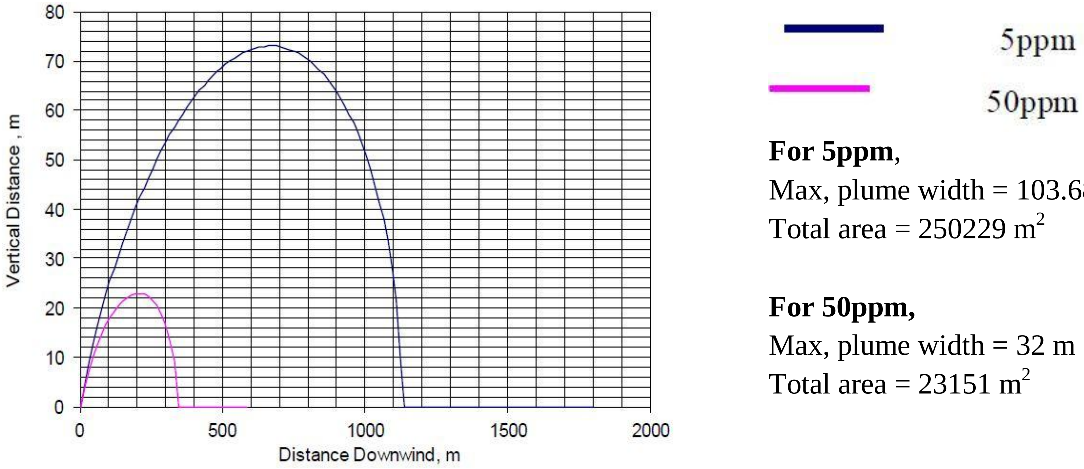

Fig.4. Dispersion of Hydrogen Chloride

For 5ppm,
Max, plume width = 103.68 m
Total area = 250229 m^2

For 50ppm,
Max, plume width = 32 m
Total area = 23151 m^2

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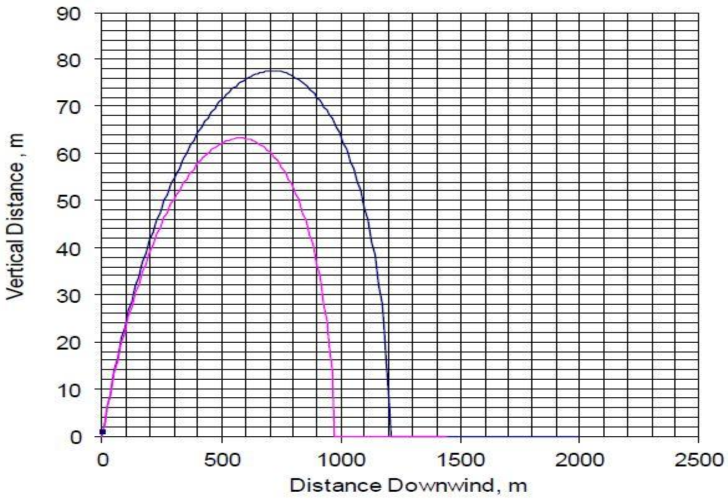

Fig.5. Dispersion of Carbon monoxide

For 25ppm
Max, plume width = 59.73 m
Total area = 79999m^2
For 200ppm
Max, plume width = 21 m
Total area = 9528m^2
For 1500ppm
Max, plume width = 7 m
Total area = 1194 m^2

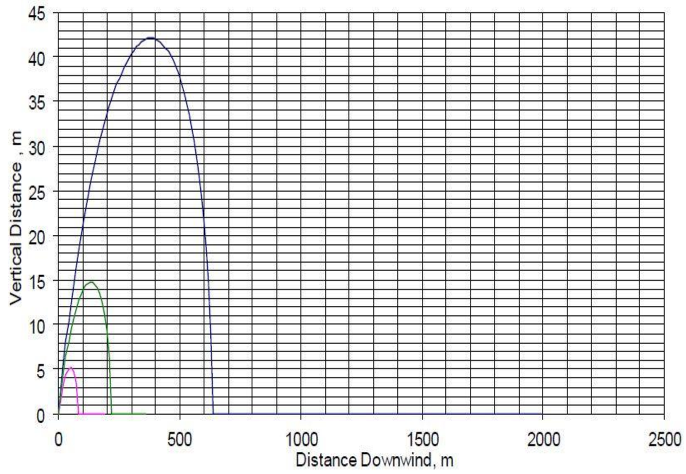

Fig.6.Dispersion of Aluminium Oxide

For 10 mg/m^3
Max, plume width = 110 m
Total area = 79999 m^2

For 15 mg/m^3
Max, plume width = 90 m
Total area = 9528 m^2

V. CONCULSION

Concentration isopleths are obtained by using simple Gaussian Dispersion mathematical equations. Many of the modern, advanced dispersion modelling programs include a pre-processor module for the input of meteorological and other data, and many also include a post-processor module for graphing the output data and/or plotting the area impacted by Exhaust gases. This simple quantitative analysis and dispersion of Toxic exhaust gases will give us first-hand information about dispersion path and distance for required concentration. Many small hazardous chemical handling industries can be benefited by refining the above calculation method according to their need to derive safe corridor during the release of hazardous gases. This study further enhances to minimize the effect of exhaust gases by using Liquid scrubber or Spray scrubber and to reach a safe limit of exhaust gas concentration over the surrounding environment.

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