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PHYSICAL MODELING OF ATMOSPHERIC DISPERSION OF HEAVY GASES RELEASED AT THE GROUND OR FROM SHORT STACKS

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Abstract. The past decade has seen a significant increase in the quantity of toxic or hazardous gases transported or stored under conditions which may result in a denser-than-air gas upon escape. Motion in the atmospheric boundary layer can be simulated in boundary-layer wind tunnels with sufficient accuracy to permit realistic scaling of escape hazards, pretest planning for field experiments, and a post-test opportunity to extend the value of limited field measurements.

Concentration measurements have been evaluated for bent-over plumes during releases in quiescent and crosswind conditions. Expressions were developed for plume rise height, "touchdown" distance and concentration variations. Heavy gases released at the ground surface exhibit a "pancaking" behavior.

Introduction

Laboratory simulation of negatively buoyant emissions into the earth's boundary layer is a valuable predictive tool to describe the motions of potentially hazardous chemicals such as propane, butane, chlorine, liquified natural gas, freon, etc. In this paper are discussed some of the simulation criteria, special instrumentation, and results of wind tunnel investigations of dense plume behavior. Such wind tunnel data can be correlated in a manner that yields an emperical prediction of vapor dispersion from full scale releases; nonetheless, certain facility and gas specific limitations must be recognized when interpreting an experimental program.

Prior Experience: Laboratory Simulation of Dense Gas As Cryogenic Spills

Dense gas plumes may result whenever the fractional density ratio, Δ, is greater than zero, i.e.

$$\Delta = -\left(\frac{C_{p_o}}{C_p}\right)\left(\frac{T-T_o}{T_o}\right) + 1 - \left(\frac{28.9}{m_o}\right) + \left(8\,\frac{\dot{M}w}{\dot{M}_o}\right) \qquad (1)$$

where C_p is a specific heat capacity at constant pressure, M_o is the mean molecular weight of the effluent, and $\dot{M}_w$ and $\dot{M}_o$ are the mass flux of liquid water and total mass flux of the effluent respectively. If $\Delta > 0$ the plume is heavier than air and may fall to the ground rather close to the source if

$$Fr = \frac{U}{\sqrt{g\Delta d_o}} < C \tag{2}$$

where C lies between 0.7 to 7.7 depending on surface roughness, wind speed and stratification condition. Prediction of the behavior of dense plumes is also often aggravated by the influence of surface interaction, heat transfer, latent heat release, and a transient character.

A number of controlled laboratory experiments have been prepared previously to evaluate the significance of density on gaseous plume dispersion. Sakagami and Kato measured diffusion and vapor rise from a small 5 x 10 cm LNG well in the floor of a 50 x 50 cm cross-section x 200 cm length wind tunnel.[1] They confirmed a tendency for the gas to remain concentrated at ground level. Boyle and Kneebone released LNG on water, precooled methane, and propane in a specially built 1.5 x 1.2 m cross-section by 5 m long asbestos-wall wind tunnel.[2] No attempt was made to scale the atmospheric surface layer velocity profile or turbulence. They concluded room-temperature propane simulated a LNG spill quite well, but the pre-cooled methane runs lofted suggesting to the authors incorrect release temperature or exaggerated heat transfer from the ground surface. Hoot and Meroney considered point source releases of heavy gases from short stacks in wind tunnels.[3] Hoot and Meroney found that releasing ground level gases with specific gravities as great as 3.0 only slightly shifted the decay of maximum concentrations with distance despite significantly different plume cross-sections. Hall considered transient and continuous releases on a rough surface (plume height - roughness height) and on up- and down-hill slopes.[4,5] Hall reported shallow, wide plumes whose shapes were considerably altered by 1 in 12 ground slopes.

Tests were conducted by Neff et al. in wind tunnel facilities to evaluate the rate of dispersion and the extent of downwind hazards associated with the rupture of typical large LNG storage tanks.[6] Concentrations and temperature measurements, and photographic records were obtained for different wind speeds, wind direction and constant boiloff rates under both neutral and stable atmospheric stratifications. Subsequent measurements by Meroney et al. examined transient releases in similar configurations as well as dense plumes on uphill slopes, and buoyant plume lift off situations.[7,8] Different model release gases were used to simulate the behavior of the cold methane plume--heavy isothermal gas mixtures (CO_2, Freon-12 and air, or Argon) or light-cold mixtures (He and N_2).

Currently research on LNG spill behavior over irregular terrain is being performed at Colorado State University for the U.S. Coast Guard and Gas Research Institute, USA.[9] Small scale models of the LNG Release Pond and surrounding topography at China Lake Naval Weapons Testing Center, California, are being examined in a meteorological wind tunnel. Mean and transient concentration contours have been mapped. Overall plume geometry and behavior have been recorded photographically. Results will be used to plan a field experiment and validate tunnel methodologies.

Laboratory Simulation of Dense Plumes

The reliability of the use of wind tunnel shear layers for modeling atmospheric flows has been demonstrated by several investigators.[10] Specific problems associated with the dispersion of cold natural gas plumes have been previously discussed by Meroney et al.[11,12]

Wind tunnel flow characteristics and physical size are such that most of the requirements for similarity with the atmosphere can only be approximated with varying degrees of accuracy. This does not eliminate the possibility of making useful studies of diffusion by means of small-scale models but limits the range of length scales and thermal conditions for which the studies are feasible. Each similarity requirement will be examined in an effort to determine the necessary approximation imposed by the physical model and the resulting limitations imposed upon a dispersion study.

Grouping independent variables which govern dense vapor dispersion into dimensionless parameters with air density, ρ_a, wind velocity at reference height, U_H, and reference height, H, as reference variables and where Q is volume source rate of the dense gas and ρ_g is dense gas density yields

$\dfrac{U_H H}{\nu}$ - Reynolds number

$\dfrac{\rho_a U_H^2}{g(\rho_a - \rho_g)H}$ - Modified Froude number

$\dfrac{\rho_g Q^2}{\rho_a U_H^2 H^4}$ - Momentum ratio

$\dfrac{\rho_g - \rho_a}{\rho_a}$ - Gas density ratio

$\dfrac{Q}{U_H H^2}$ - Non-dimensional spill rate

$\dfrac{g(T_H - T_o)H}{T\, U_H^2}$ - Bulk Richardson number of inverse atmospheric Froude number

$\dfrac{\delta}{H}, \dfrac{D}{H}, \dfrac{h}{H}, \dfrac{k}{H}$ - Various length scale ratios associated with shear layer thickness, δ, dike or building diameters, D; structure height, h; and roughness length, k.

For a model test to be completely representative of the full-scale event, values of at least these ten dimensionless numbers plus similarity in approach flow velocity and turbulence profiles should be the same in the model test as at full-scale. Since it is not possible to retain exactly the same values of all these numbers at full- and model scale some latitude must be tolerated. (Indeed in many cases the full-scale values are not even well defined.) One may accept variation in these parameters to the extent that such lassitude does not jeopardize the representativeness of the model.

The Reynolds number cannot be made equal for model and prototype for scales ranging from 1:100 to 1:600. Fortunately equality is not required if the magnitude and quality of the shear layer turbulence is similar to the full-scale--hence the use of specially designed meteorological wind tunnels.[10] It is possible to obtain full-scale values of the remaining non-dimensional parameters by reducing the reference velocity, U_H, to very low values (of the order of 0.2 m/s to simulate a 3 m/sec full-scale wind) and increasing the atmospheric temperature difference $(T_H - T_o)$ as necessary. In some cases investigators modify the density ratio $(\rho_a - \rho)/_g\rho_a$ to permit the use of larger and more convenient values of U_H.[4,13] Unfortunately this also modifies inertial effects, time scale ratios, and volume dilution rates so this is not proposed herein.

Previous experiments by Hoot and Meroney, Bodurtha, Van Ulden, and Boyle and Kneebone have confirmed that the Froude number is the parameter which governs plume spread rate, trajectory, plume size and entrainment when gases remain negatively buoyant during their entire trajectory.[3,14,15,2] In the case of spills of LNG buoyancy of the plume will be a function of both mole fraction of methane and temperature. Thus, depending upon the relative rate of entrainment of ambient gases versus rate of thermal transport from surrounding surfaces the state of buoyancy may vary from negative to positive.

Earlier measurements for cold methane releases now suggest that heat transfer effects may be small over the significant time scales associated with non-calm situations (i.e., $U_p > 1$ m/sec); hence gas density should be adequately simulated by isothermal high molecular weight gas mixtures.[6,7] This agrees with the result independently reported by Boyle and Kneebone that room temperature propane simulated an actual LNG spill quite well.[2]

Facilities and Equipment

Simulation of the atmospheric surface layer in Bounday Layer Wind Tunnels has been considered in some detail by previous authors. Special procedures required to inject cold gas plumes are considered by Meroney et al.[12] Representation of transient sources require additional tools recommended below.

Variable Source Rate Simulation

To obtain an accurate prediction of the extent of hazard associated with the spill of a low vapor pressure liquid such as LNG, ammonia, or Freon, the model should simulate the variable boiloff rate of the gas characteristic to that of the spill configuration.

Variable gas flow rate curves may be obtained by use of a programmed cam to close a micrometer needle value controlling the flow of simulation set at a predetermined rate.

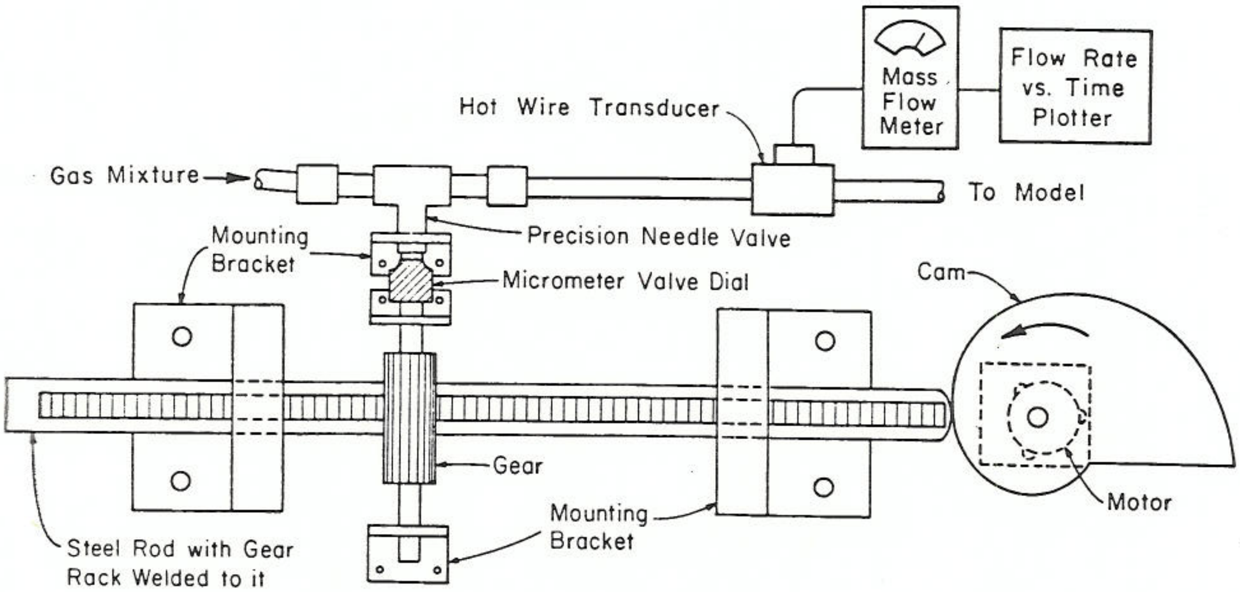

Figure 1. Variable Flow Rate Control Valve

Transient-Concentration Instrumentation

The transient nature of most chemical spills to be simulated necessitate the use of a fast response, temperature compensated concentration transducer. An aspirated dual-film probe was designed recently at Colorado State University. As noted in Figure 2 dual films operated at different current levels permitted compensation for temperature drift, while a flared inlet reduced the noise of pressure fluctuations. Calibration suggests a noise level of 0.1% by volume CO_2 or Argon and an upper frequency response of 1000 Hz.

Variable-Area-Source Release

When low vapor pressure liquids spill on an uncontained surface, density causes the liquid to grow radially outward until all the liquid is vaporized. Generally this growth is thought to be linear with time. Since no cryogenic fluid is generally used in model tests, the resultant variable area nature of the release must be simulated by means of auxiliary equipment installed beneath the wind tunnel floor.

A variable area source devise has been constructed for the current China Lake spill series. As shown in Figure 3 it consists of a contoured honeycomb surface together with a mercury filled bladder. The device has been constructed at a diameter of 0.25 meters; however a larger version may be possible. A simple alternative for the larger size releases is a set of concentric anuluses metered by flowraters and monitored by cam operated solenoid valves.

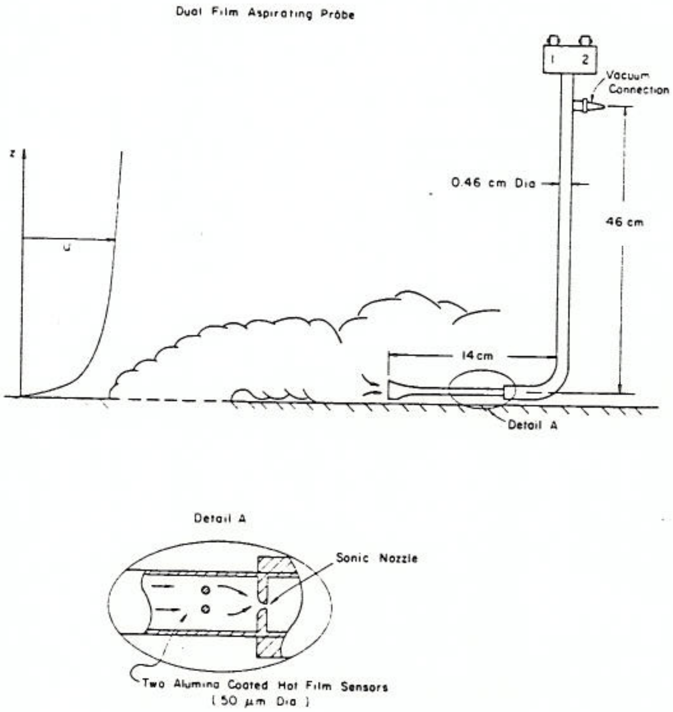

Figure 2. Dual Film Aspirating Concentration Probe

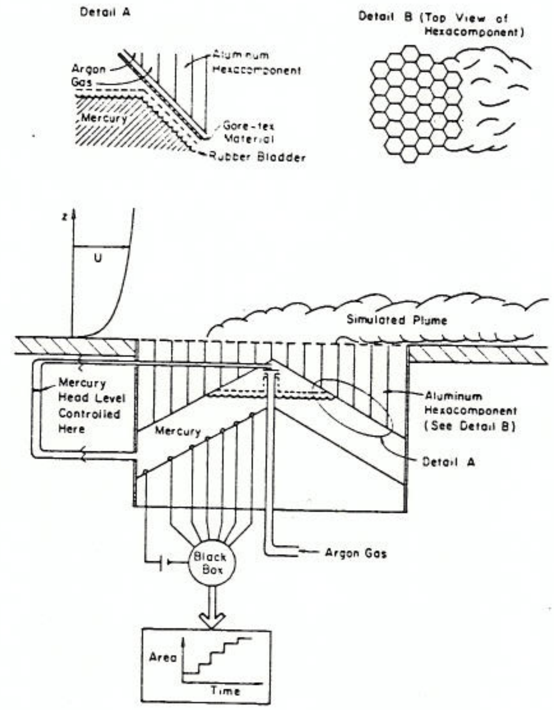

Figure 3. Variable Area Source Model

Test Program Results

The purpose of this paper is to report the character of results of utilizing wind tunnels as a tool to study dense gas released rather than present comprehensive results. Extended discussions of the dense gas release cases examined at Colorado State University are available in report format.[6,7,8,9,16,17]

Dense Plume Dynamics Associated With Structures, Ground Level Release

Density differences were observed by Hoot and Meroney to have significant effect on the downstream diffusion patterns of a ground source.[17] Lateral spread rate increased and vertical spread rate decreased in the vicinity of a release over that displayed by a neutrally buoyant plume as shown in Figure 4. The effect of variation of maximum centerline concentration with distance was primarily multiplicative. Echols prepared corrections to Gaussian plume calculations from this data to provide corrections to conventional Gaussian plume predictions when estimating hazards due to hydrogen sulphide release.[18]

When dense gas clouds result from a breach in a storage tank, the heavy gas may rapidly spread laterally outside the aerodynamic wake region downwind of the tank. In such cases the portion of the plume outside the wake will not be mixed by the turbulent intensity excess present in the wake region, and bifurcated plume profiles will exist at ground level as suggested by the sketch in Figure 5. The tank and bund structure may mix gases vertically immediately downwind as shown in the figure; however, surface concentrations generally vary with distance in a manner noted by Figure 4.

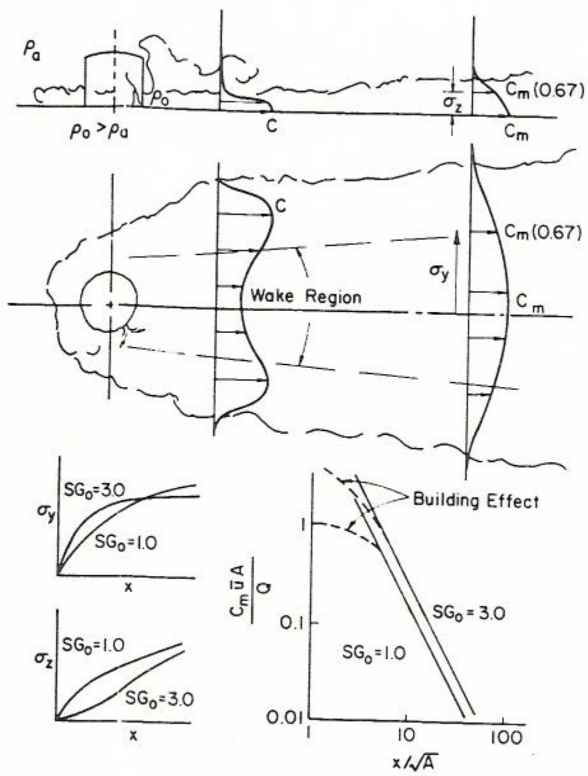

Figure 4. Dense Plume Dispersion Ground Source Release

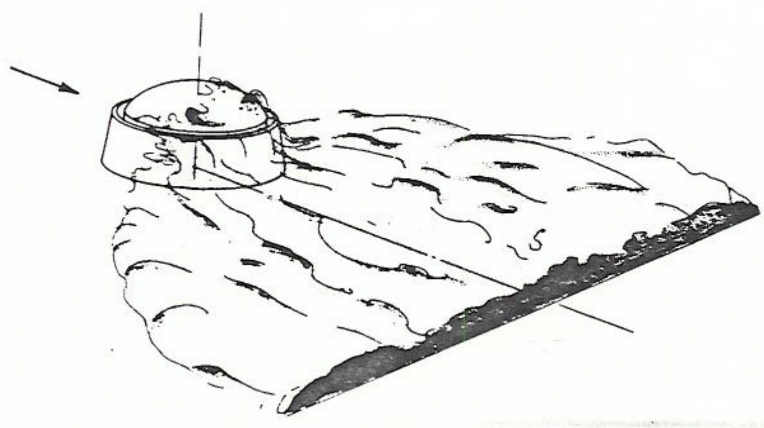

Figure 5. Dense Gas Spreading Downwind of a Tall Dike About a Storage Tank

Dense Plume Dynamics Associated With Structures - Elevated Releases

Hoot and Meroney proposed a method to estimate surface concentrations based on emperical tuning of an analytical plume theory.[3,17] The components of the analysis requires one to first estimate plume rise, Δh, as

$$\frac{\Delta h}{d_o} = 1.32\ (S.G.)^{2/3}\ (F_{RH})^{2/3}\ (R), \qquad (3)$$

where $S.G. = \rho_o/\rho_a$

$R \quad = w_o/u$

$F_{RH} = U/\sqrt{g\Delta d_o}$, and

downwind distance to maximum plume rise, $\bar{x}$, as

$$\frac{\bar{x}}{d_o} = (S.G.)\ (F_{RH})^2\ (R)\ . \tag{4}$$

Touchdown distance, x_{TD}, may be evaluated from

$$\frac{x_{TD}-\bar{x}}{d_o} = 0.56\left[\frac{\left(\frac{h_s}{d_o} + 2\frac{\Delta h}{d_o}\right)^3 - \left(\frac{\Delta h}{d_o}\right)^3}{R}\right]^{1/2} \cdot F_{RH} \tag{5}$$

(Symbols are defined in Figure 6)

Note that as $u \to 0$, $F_{RH} \to 0$, $\bar{x} \to 0$, $\Delta h \to 0$ and $x_{TD}/h_s \to 3\ F_{RH}$. The constant, 3, compares well to the value 4.5 proposed by Briggs based on Bodurtha's visualization experiments.[19]

At touchdown the surface concentrations are of the order

$$\frac{C_{TD}\ u h_s^2}{Q} \simeq \left(\frac{2\Delta h + h_s}{h_s}\right)^{-2} \tag{6}$$

Concentrations decrease from their touchdown values at a negative 0.65 power of distance, x, until the curve intercepts the -1.7 slope behavior of a ground source as shown in Figure 6.

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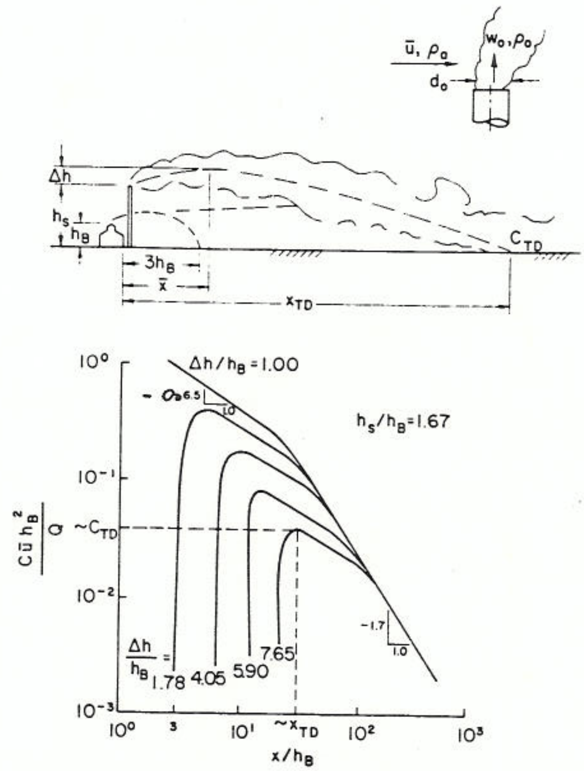

Figure 6. Dispersion of Dense Plumes From Short Stacks

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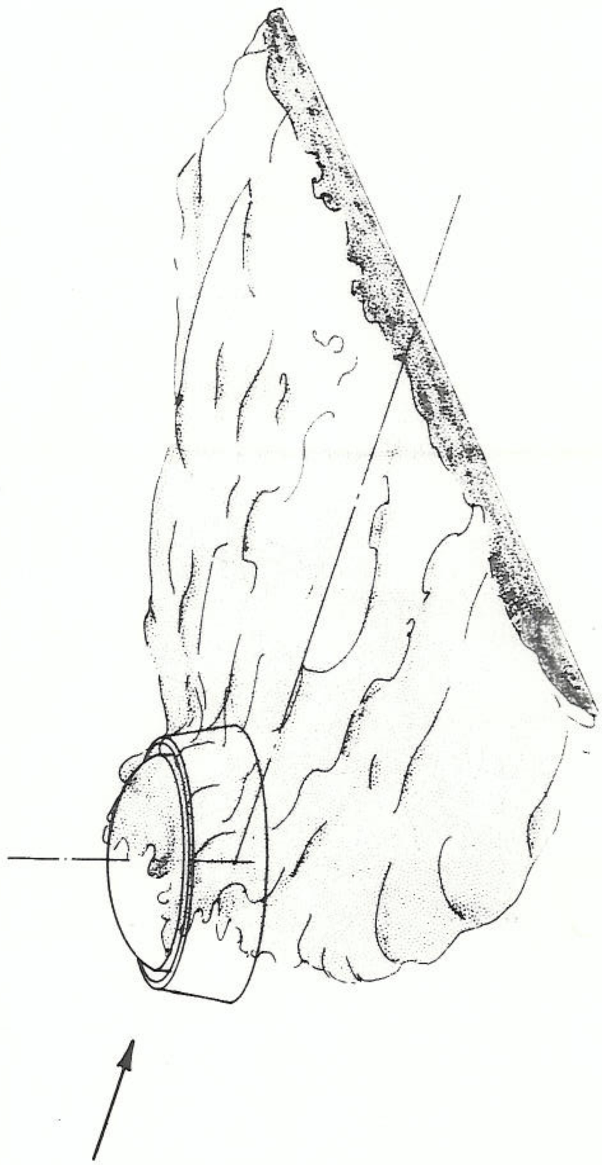


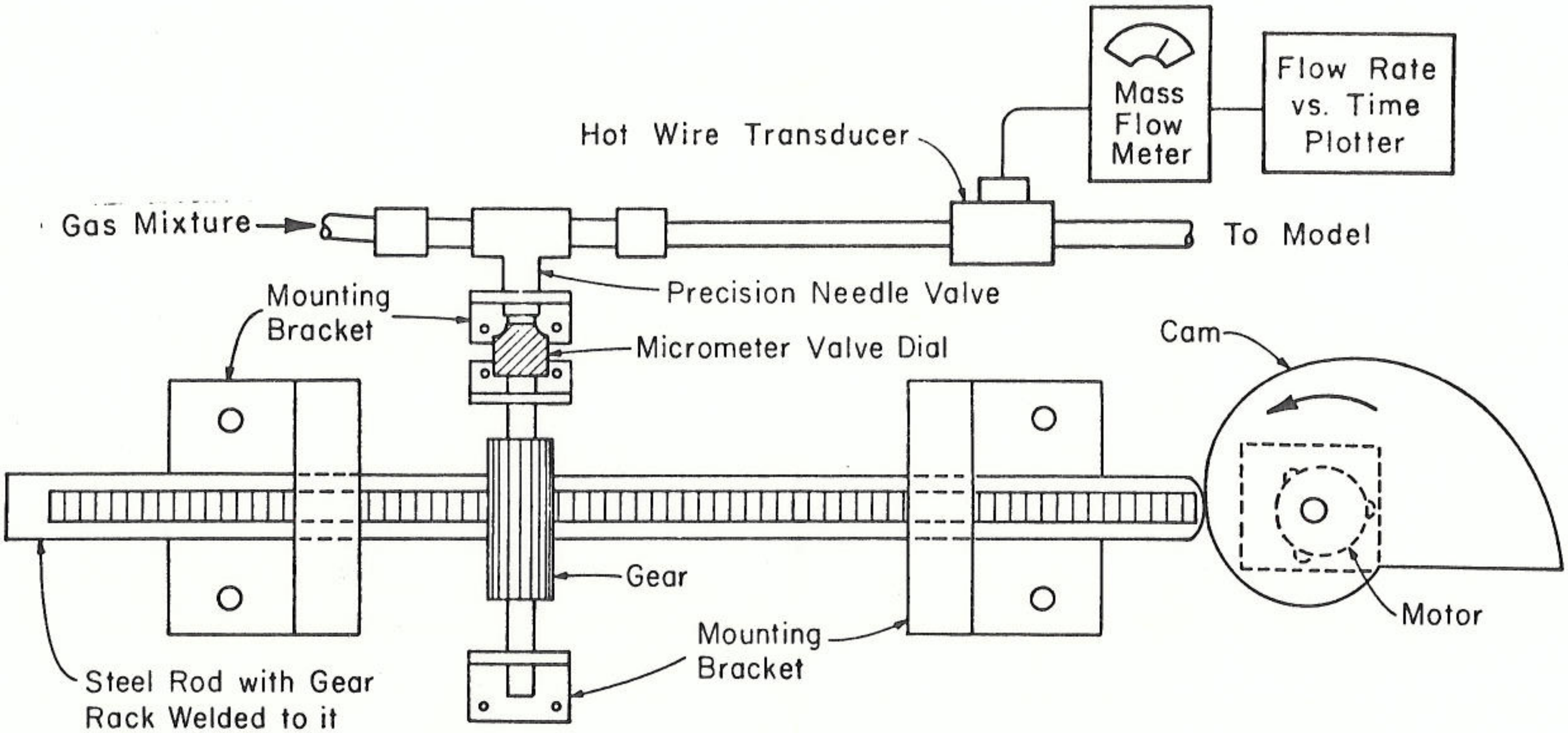
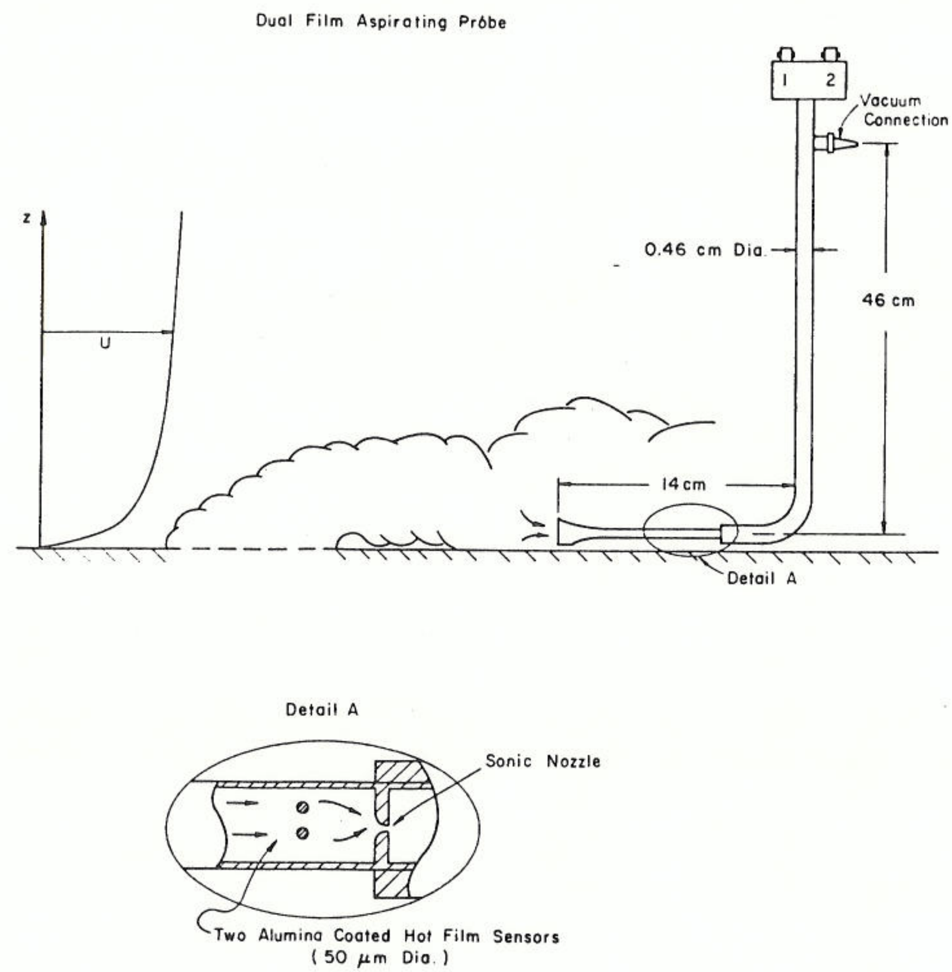


Figure 4. Variable Flow Rate Control Valve

← 6½" →



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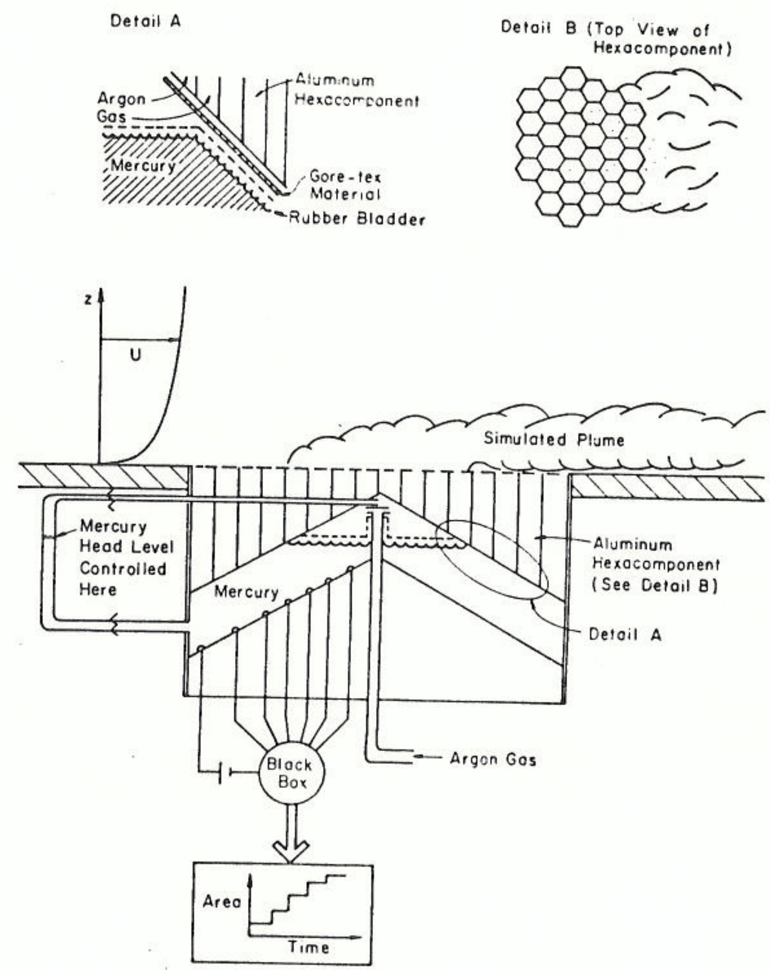

Figure 3. Variable Area Source Model