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GUIDELINES FOR FLUID MODELING OF DENSE GAS CLOUD DISPERSION

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Summary

Fluid modeling experiments can predict the behavior of complex dispersion phenomena associated with the dilution of flammable or toxic dense gases after inadvertent release. Such studies are desirable because variables can be controlled at will with great savings in time and expense over full-scale tests. The reliability and value of fluid modeling experiments will depend upon proper applications of similitude laws, the selection of appropriate instrumentation and test facilities, and the documentation of the results. This paper proposes guidelines for future fluid modeling experiments of dense gas cloud dispersion. Performance envelopes are presented which bracket the "safe" regions in similitude parameter space for reliable model results. Recommendations are made for a minimum experimental program and associated documentation.

1. Introduction

It is important that accurate predictive models for flammable or toxic vapor cloud behavior be developed, so that the associated hazards of transportation and storage may be realistically assessed. Thermal effects, topography, the presence of obstacles and spray curtain mitigation devices can affect the dispersion of dense gas clouds. Fluid or physical modeling studies are often desirable because such variables can be controlled at will, with great savings in time and expense over full-scale tests. The physical model inherently includes fluid physics for which only limited understanding can presently be incorporated in numerical models.

However, certain constraints exist on a physical model's ability to predict plume behavior. These constraints are due to the limited range of transport properties of air and water, the inherent characteristics of fluid turbulence, and the size range of available fluid modeling facilities. The primary intent of this paper is to stipulate the conditions under which reliable fluid modeling experiments on dense gas dispersion can be performed. This paper reviews the characteristics of various fluid modeling wind tunnels and hardware. It also

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suggests check lists and quality control criteria necessary to permit independent duplication of experiments by other investigators. Since not all simulations are physically possible in conventional wind or water tunnel facilities, the concept of performance envelopes is introduced. Combined with some preliminary experimental design, these envelopes should help define the productive and feasible test plan.

1.1 Preliminary experiment design

A fluid modeling experiment should be constructed based on the intended use of the resulting data. The feasibility, value, cost, and time required by an experimental program will depend on pre-stipulated criteria concerning experimental complexity, resolution, and accuracy. It is not uncommon to impose unnecessary and stringent conditions on a numerical or fluid model due to unfortunate wording of the original motivation for the experiment. For example, in a hazard situation the following questions might be asked, but each demands quite a different model response:

1. Beyond what distances from a source will hazardous conditions not exist under defined spill conditions?
2. Beyond what distances from a source will hazardous conditions occur more than time *T* with a probability *P*?
3. Beyond what distances from a source will hazardous conditions occur more than time *T* with a probability *P*? The distances must be specified with only a possibility of error, *E*, that the distance is in error more than *D*.
4. What are the maximum values of concentrations which occur spatially around the source?
5. What is the actual time variation in concentrations which occur spatially around the source?

In other words, follow a practice of reasonable goals, that is:

1. Avoid stipulating acquisition of more information than you really need to make a decision.
2. Select credibility criteria for data statistics which are realistically obtainable (e.g., trying to avoid a small Type II error with great confidence results in very large data requirements). Absolute assurance of safety is a myth in a stochastic world.
3. Evaluate whether the time and effort in the experimental program is commensurate with expected results.
4. Do not overcomplicate the laboratory experiment. By including all possible perturbing forces, one is often unable to identify driving physical mechanisms.
5. Estimate probable results of the more expensive numerical models and fluid modeling experiments in advance, using box or slab-type numerical models. Unnecessary or uninformative experiments can be eliminated.

6. Consider a conservative approach. That is, if no hazard exists for some situations, even when exaggerated scale accidents are examined, there is no need to know exact concentrations. This permits the experimenter to focus effort on the critical scenarios.

These matters are discussed at some length in papers by Hartwig and Flothman [1], Wiersma [2], and McQuaid [3]. The degree of satisfaction derived from a laboratory or numerical model will depend upon the original expectations and the clear specification of objectives.

2. Data acquisition and analysis

The characteristics and capabilities of the fluid modeler's technical hardware determine whether program objectives can actually be attained in laboratory facilities. The present section considers the size and performance characteristics required of the facility and instrumentation. The material is primarily written with a view toward wind tunnels, but the principles also apply to water channels.

2.1 Fluid modeling laboratory facilities

Oral or written reports have been made about the results of dense gas dispersion experiments in at least 15 laboratories. Table 1 describes the somewhat limited information which could be readily extracted concerning the type and size facilities used. Most wind-tunnel facilities used have been open-circuit test sections without thermal stratification. None of the equipment appears to have been designed specifically to operate at the low wind velocities frequently required for LNG spill simulation (i.e., < 0.5 m/s). Water type experimentation has tended to emphasize flow visualization with dyes; however, concentration measurements using conductivity probes would be possible. A variety of experimental configurations have been examined as noted in Table 2. A number of experiments are still considered proprietary in nature; hence, the results are not available to the scientific community.

Air versus water systems

The selection of an air versus water medium for modeling LNG dispersion will depend on the availability, economics, and the type of problem to be studied. The kinematic viscosity of water at normal room temperature is a factor of 16 less than that of air; hence, at the same scale and fluid speed the Reynolds number may be 16 times higher for a water experiment. Unfortunately, because water is so much heavier than air, structural and pumping requirements result in water facilities which tend to be much smaller than wind tunnels. Thus, the larger Reynolds number potential of water facilities is seldom attained.

Sometimes investigators have used water drag tanks to examine flow over hills or other obstacles. This method is really not appropriate for ground level

TABLE 1

Participants in physical modeling

Groups	Location	Facility	Type
Wind tunnels			
Hall et al. (1974, 1979, 1982, 1985)	Warren Springs U.K.	4.3m×1.6m×22m	Open
Meroney et al. (1973, 1976, 1977, 1979, 1980, 1981, 1982, 1983)	Colorado State University U.S.A.	1.83m×1.83m×24m 2.44m×3.66m×18m	Closed Open
Ohba (1978)	Mitsubushi Industry Nagasaki, Japan		Open
Lohmeyer et al. (1980, 1982)	University of Karlsruhe F.R.G.	0.5m×2m×5m	Open
Builtjes et al. (1980, 1982, 1982, 1984)	T.N.O. Apeldoorn, The Netherlands	1.2m×2.65m×6.8m	Open
Krogstad (1980)	SINTEFF Trondheim, Norway	Air flume	
Colenbrander et al. (1980-1984)	SHELL Research laboratory Amsterdam, The Netherlands		
Reithmuller (1982)	VonKarman Institute Belgium		
Bradley and Carpenter (1983)	National Maritime Institute U.K.	2.4m×4.8m×15m	
Schatzman et al. (1984)	University of Hamburg F.R.G.		Open
Water tunnels and flumes			
Britter (1980)	Cambridge University U.K.		Open
Hanssen (1981)	Norwegian Hydro	0.5m×2m×5m	Closed
Wighus (1982)	Norway		
Alessio (1983)	University of Torsino Italy		
Bradley and Carpenter (1983)	Grenoble France	0.75m×3m×15m	
Cleaver et al. (1983)	University of Liverpool U.K.	0.84m×1.4m×4m	Closed

releases of LNG, because the uniform approach profile simulated is not equivalent to the shear flow found near the earth's surface.

Air, with its low heat capacity, is comparatively easy to stratify using heat. A few special meteorological wind tunnels have been designed to reproduce some aspects of the stratified atmospheric boundary layer (Meteorological Wind Tunnel, Colorado State University, U.S.A.; Environmental Wind Tunnel, Mitsubushi Industries, Nagasaki, Japan; Meteorological Wind Tunnel, Bundeswahr Hochschule, Munich, B.R.D.). Stratification in water is generally produced by layers of mixtures of water and salt. Large water facilities which recirculate stratified fluids by conventional pumps are essentially impractical; since the pumps which produce recirculation tend to destroy the stratification.

TABLE 2

Physical modeling experiments at dense gas dispersion

Organization	Idealized continuous	Idealized finite	Idealized instantaneous	Tanks and dikes	Terrain	Fences	Ships	Water spray	Air curtains	Stacks
Warren Springs, U.K.	1974,79	1974,79	1982,85		1974					
Col. State U., U.S.A.	1982,83	1982	1982	1976,77,80,82	1977,81	1981,82		1983,84		1973,80
Mitsubushi Ind., Japan				1978				1978		
Cambridge U., U.K.	1980									
U. of Karlsruhe, F.R.G.			1980							
T.N.O., Apeldoorn, Neth.	1980		1984,85	1980,82		1980	1980			
SINTEF, Norway			1980							
SHELL Research, Neth.	1980–84						1980			
Norwegian Hydro, Norway				1982						
Von Karman Inst., Belgium				1982						
U. of Torsino, Italy					1981					
Nat. Maritime Inst., U.K.			1984	1983	1983					
U. of Arkansas, U.S.A.			1983							
U. of Liverpool, U.K.	1983					1983				
U. of Hamburg, F.R.G.			1985							

In air it is possible to obtain specific gravity variations ranging from 1.0 to 5.0; hence, a significant distortion of buoyancy forces is possible. In water most experiments using salt as a density ingredient have been performed with specific gravities between 1.0 and 1.1. Indeed, the highest relative density obtainable in a water soluble solution is about 1.4. Thus, to model spills of source density greater than this (for example a pure Freon-12 spill ($SG = 4.17$), modified Froude number modeling must be used in a fashion reverse to that of a wind tunnel (i.e., reducing the water velocities to compensate for an insufficient spill source density, and consequently lowering the operating Reynolds number yet further) [4].

Consideration of the characteristics of each type facility leads one to conclude:

1. The ease and convenience of operating wind tunnels and associated measuring equipment and the ability to adequately simulate the neutral and stratified atmospheric boundary layer make the wind tunnel superior to the water tunnel or water towing tank for scale studies of LNG spill phenomena.
2. The excellent visualization capabilities and the increase in Reynolds number provided by water facilities suggest they are measurement platforms best used to study basic dense fluid flow and dispersion when quantitative measurements of velocities and turbulence are not so important.

2.2 Wind profile and turbulence measurements

Hot-wire, hot-film, and pulsed-wire anemometers are available to measure wind speed and turbulence in wind tunnels. Hot-film anemometers are used in water, but require a great deal of care to get reliable results. Pitot tubes are rarely usable at the low speeds required during dense gas dispersion research in wind or water facilities. Laser anemometry at low flow velocities requires expensive equipment, and adequate traverse systems are rarely installed in the larger meteorological facilities.

Flow speeds required during LNG spill simulations are often less than 50 cm/s. Most conventional hot-wire or hot-film equipment are not intended to be used at such low velocities. Care must be taken to achieve reliable calibration, to correct for low-speed probe non-linearities, and to avoid electronic noise in the low-signal, low-wind-speed environment. The pulsed-wire anemometer is especially useful in low speed and reversing flows, as it is capable of detecting the direction of flow. Unfortunately, some investigators have found the pulsed-wire anemometer sensitive to temperature variations in stratified flows.

Most laboratory flows used to examine dense fluid behavior have not been well documented with respect to turbulence characteristics. The measurements of Neff and Meroney [5] suggest that near ground velocity profiles have a significant effect on dense plume dispersion. Future studies should make every effort to measure accurate wind speed profiles, rms turbulence profiles, spectra, and integral scales.

2.3 Visualization and concentration measurements

By using different colors and densities of dye, hydrogen bubbles, potassium permanganate crystals, or neutrally buoyant particles a wide variety of visualization techniques is available in water tunnels. Low flow speeds permit excellent visualization and photographs of flow patterns. The comparable smoke type visualization procedures used in wind tunnels are notoriously cantankerous, dirty, and sometimes toxic. Nonetheless, the physical insight gained during flow visualization always justifies the effort. Television systems provide a recording medium for the visualization results which are convenient and inexpensive. Digitization and processing of television images and patterns can now be accomplished inexpensively using desktop computers.

Concentrations can be examined from a variety of simultaneous sources in wind tunnels using flame-ionization or electron-capture techniques. Aspirated hot-wire anemometers or *in-situ* flame-ionization devices can follow concentration fluctuations to at least 60 Hz. Salts in conjunction with conductivity meters, acids with pH meters, temperature with thermistors, and dyes with colorimeters and fluorometers have been used as tracers for quantitative measurements of concentration in water. Conductivity probes in water typically respond to frequencies of 10–20 Hz.

2.4 Averaging times and sampling rates in the laboratory

One may pose at least two questions with respect to averaging times associated with laboratory measurements. First, how long should one sample in the laboratory to obtain a stable average? And second, to what averaging time is the laboratory measurement equivalent?

Let us consider a prototype measurement made at a height of 10 m for wind speed of 3 m/s. Assuming a typical eddy scale for vertical movement of 10 m, one finds that a 15 min average allows one to sample 270 perturbations. Given a 1:200 scale, such that the equivalent height in the boundary layer is 5 cm, and a model wind of 0.5 m/s, then 30 s in the laboratory will sample an equivalent number of eddies. Of course the large (long time) eddies which result in nonstationarity in the atmosphere and the consequent long tails to probability distributions are missing in the laboratory; thus, laboratory turbulence only presumes to represent atmospheric behavior below the “spectral gap”. It is also the case that the smallest scale of eddies are missing in reduced scale models due to low Reynolds number effects. This may be of particular significance to heavy gas releases where the gas cloud is ground-based and of small depth, so it may only encompass a small range of eddy scales in the vertical plane.

Lumley and Panofsky [6] showed how averaging time requirement can be related to turbulence scales. Presuming a stationary laboratory situation and a turbulent shear flow it is appropriate to begin by considering the turbulence present to be a Gaussian process. The variance, σ^2, of the difference between the ensemble (true) average of a quantity and the average obtained by integration over the averaging time, T, for some fluctuating quantity, F, is

$$\sigma^2 = 2\overline{f'^2}\, I_F/T \tag{1}$$

where I_F is the integral time scale of F, $f' = F - \bar{F}$, and $\overline{f'^2}$ is the ensemble variance of F about its ensemble mean. Since the fractional error, ϵ, is given by $\epsilon^2 = \sigma^2/\bar{F}_2$, then the averaging time, T, required to stay below ϵ is

$$T = 2\ (\overline{f'^2}/\bar{F}^2)\ (I_F/\epsilon^2) \tag{2}$$

Let $F = u = \bar{u} + u'$; $\bar{F} = \bar{u}$; $f' = u'$; $\overline{f'^2} = \overline{u'^2}$. Near a wall in a turbulent boundary layer one typically finds $\sqrt{u'^2}/u = \mathrm{O}(0.1)$ and $I_u = \mathrm{O}(\delta/u)$; thus

$$T_u = 2\ (0.1)^2(\delta/u)/\epsilon^2 = 0.02\ (\delta/u)\,\epsilon^2 \tag{3}$$

Hence, for $\delta = 1$ m and $u = 0.5$ m/s then $T_u = 0.04/\epsilon^2$. When ϵ is 1%, 5% or 10% then T_u will be 400, 16, and 4 s, respectively.

A similar result will hold for mean concentrations; however, the required averaging times for second and higher moments (i.e., $\overline{u'^2}$, $\overline{c'^2}$, $\overline{u'v'}$, $\overline{u'w'}$, $\overline{w'c'}$, $\overline{u'^4}$, etc.) will normally take much longer. The method requires information about the integral scales of the variable F, but this is usually unknown for higher order moments. So further estimates by this method would be largely conjecture.

Alternatively, for normally distributed fluctuations, estimates of required sample sizes for the determination of mean quantities within pre-specified limits with stipulated levels of confidence can be calculated by the student t-test method. For concentrations distributed normally about some mean value, the numbers of samples required for the determination of mean concentration and concentration intensity are

$$n_C = t^2\ (\overline{c'^2}/C^2)/[(\Delta C)^2/C^2] \tag{4}$$

and

$$n_{c'} = t^2/[2(\Delta(\overline{c'^2})^{1/2})^2/(\overline{c'^2})]$$

where n_i is the number of samples required to ensure that the estimates of mean concentration, C, and concentration intensity, $\overline{c'^2}$, are within a precision of $\pm\Delta C$ and $\pm\Delta(\overline{c'^2})^{1/2}$, respectively, of the actual ensemble values. Symbol t is the student t-parameter; for a 95% or 90% probability of being within the interval, the t values are 1.96 and 1.645, respectively. For example, if the concentration intensity is of order 0.1, then to determine the mean concentration within ±5% of the ensemble mean concentration with 95% probability, it would be necessary to average at least 15 samples. The concentration intensity determined with 15 samples would be within 36% of the ensemble intensity with 95% probability. Note, however, that if the concentration fluctuations are more extreme, e.g., the concentration fluctuation intensity is of order 0.5, then the required sample size is 384 and the concentration intensity would be within ±7% of the ensemble intensity with 95% probability. These estimates assume linearly independent samples, taken with error-free instrumentation. Hence, the samples must be taken from a time series far enough apart to have zero correlation.

Alternatively, one can think in terms of the number of replications required to attain a specified confidence. Carn and Chatwin [7] calculated from t-test criteria that in order to have a 90% confidence that the ensemble value of $\overline{c'^2}$ is within ±5% of its actual value requires 86 replications, whereas a 99% confidence requires 5300 experiments.

Presuming measurements are taken for a sufficiently long time in stationary laboratory flows generated in meteorological wind-tunnel facilities, then magnitudes measured should correspond to averaging over scales less than the spectral gap. Extensive comparisons between laboratory measurements in simulated boundary layers and atmospheric flows suggests the laboratory data correspond to field times of 10–30 min. Extended discussions of this subject are provided by Plate [8] and Snyder [9].

2.5 Spatial resolution of measurements

Recently, there has been considerable debate about the presence of fine concentration structure in field and laboratory plumes. Carn and Chatwin [7], Jones [10], and Hadjitofi and Wilson [11], in particular, have been concerned that peak concentrations are not actually measured because available concentration instrumentation do not have the spatial resolution to detect undiluted cloud wisps.

These authors argue that elements of the cloud distorted and dispersed by turbulence will actually remain undiluted until eddy sizes are stretched to the order of a "conduction cut-off scale", $\lambda_c = (\nu D^2/\epsilon)^{1/4}$, where ϵ is the local rate of dissipation of mechanical energy per unit mass, ν is the kinematic viscosity of air, and D is the molecular diffusivity. This length is similar to the Kolmogoroff microscale in the theory of turbulence. For gases, the conduction cut-off scale and the Kolmogoroff microscale are of the same order of magnitude, and in the atmosphere or the wind tunnel each is typically of the order of 1 mm. Instrument time response must also be fast in order to respond to an element convected by the sensor in time λ_c/u, typically 400 Hz.

Although most of the arguments are theoretical (since no instruments exist which could verify the proposed cloud structure — a nice Catch 22 situation) some indirect measurements may support their ideas. Carn and Chatwin [7] predicted large magnitudes for centerline concentration fluctuation intensities downwind of continuous sources. Fackrell and Robins [12] measured fluctuating plume behavior downstream of elevated and ground level plumes in wind-tunnel boundary layers. For elevated source size to integral scale sizes of 0.026, they produced concentration fluctuation intensities near 0.25 at intermediate distances of 20 integral scales downwind. On the other hand, Fackrell and Robins found for ground level sources that concentration fluctuation intensity had no significant dependence on source size or distance, and measured intensity values were about 0.5.

Sawford and Hunt [13] considered molecular diffusivity and instrument smoothing effects on concentration variations produced by a Lagrangian stochastic model of particle–pair motions. Over the range of conditions they considered, they found concentration fluctuation intensities of the order unity or less. Carn and Chatwin [7] responded by arguing that a one-dimensional model was not adequate to predict three-dimensional phenomena. Hunt [14] (1984) further argues that temperature scalar measurements in grid turbulence made by Warhaft and Lumley [15] show that tracers initially very close together (less than the Kolmogoroff scale distance) rapidly separate due to a combination of microscopic and eddy scale movements. Hence, filaments of the uncontaminated source material will not remain together very long.

Even if the scientific community should finally conclude that elements of an LNG spill may remain undiluted in small eddies for large distances, the issue need not necessarily increase hazard areas substantially or diminish the value of experimental measurements. There is no evidence from field ignition experiments that such small high concentration eddies are ignitable or provide ignition links to the main LNG or LPG cloud. In addition there is some evidence such high frequency eddy structure contributes minimally to concentration variance.

Hinze [16] has evaluated the effect of hot-wire length on the contribution of high frequency fluctuations to estimates of turbulent energy, $\overline{u'^2}$. Similar arguments apply for concentration variance, $\overline{c'^2}$. Assuming turbulence is homogeneous and isotropic, and that there are no spatial gradients in the mean concentration, then the transducer response of size η will be

$$\overline{e'^2} = K^2\ \eta^2\ \overline{c'^2} \tag{5}$$

but when there are spatial non-uniformities in the concentration field, then the transducer response will be

$$\overline{e'^2_{\mathrm{m}}} = 2\,K^2\ \overline{c'^2} \int_{-\eta}^{\eta} (\eta - x)\ g(x)\ \mathrm{d}x \tag{6}$$

where η is the transducer size, K is the transducer voltage response, and $g(x)$ is eddy spatial correlation. In order to correct the transducer for spatial resolution the measured values, $\overline{e'^2}$, must be corrected by the factor CF

$$\mathrm{CF} = (2/\eta^2)\ \overline{c'^2} \int_{-\eta}^{\eta} (\eta - x)\ g(x)\ \mathrm{d}x \tag{7}$$

such that $\overline{e'^2} = \overline{e'^2_{\mathrm{m}}}/\mathrm{CF}$. When $\eta \gg$ integral scale, then the correction is very large, and no turbulence is measured. When $\eta \ll \lambda_T$, the Taylor microscale, then $g(x) \simeq (1 - x^2/\lambda_T^2)$, and

$$\mathrm{CF} \simeq (1 - \eta^2/(6\lambda_T^2))^{-1} \tag{8}$$

Note that the correction is on $\overline{e'^2}$, not e'; that is, the smallest eddies may still actually be at conduction cut-off or Kolmogoroff scales. Nonetheless, one sees that if $\eta < 0.5\ \lambda_T$ then only a 4% spatial resolution error exists in $\overline{e'^2}$, and if $\eta \simeq \lambda_T$ then a 20% error in $\overline{e'^2}$ would occur.

Li and Meroney [17] measured Taylor scales between 0.015 and 0.033 m in a meteorological wind tunnel at wind speeds below 2 m/s. Neff and Meroney [5] estimated sampling areas of their aspirated hot-film katherometers to be less than 0.5 cm^2, or $\eta = 0.007$ m. Given $\lambda_T \simeq 0.02$ and $\eta \simeq 0.007$ then the instrument would measure concentration variance with only a ±2% error due to spatial resolution.

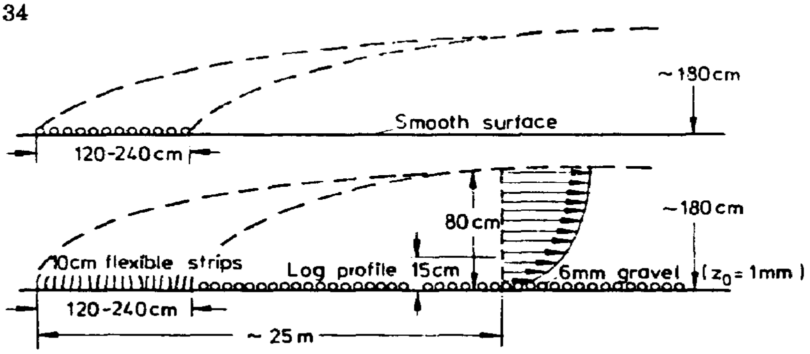
3. Wind-tunnel performance envelopes

The viability of a given simulation scenario is not only a function of the governing flow physics, but it also depends upon the availability of a suitable simulation facility and the measurement instrumentation employed. It is appropriate, therefore, to suggest bounds for the range of field situations which can reasonably be treated by physical modeling. Generally wind tunnels range in size from facilities with cross-sections of 0.5 m × 0.5 m to 3 m × 4 m. Several of these facilities are equipped with movable side walls or ceilings to adjust for model blockage. By utilizing a variety of devices such as vortex generators, fences, roughness, grids, screens, or jets a fairly wide range of turbulence integral scales can be introduced into the shear layer (see Fig. 1). Varying surface roughness permits control of surface turbulence intensity, dimensionless wall shear, and velocity profile shape. Density stratification can be induced by means of heat exchangers, use of different molecular weight gases, or latent heat absorption or release during phase changes.

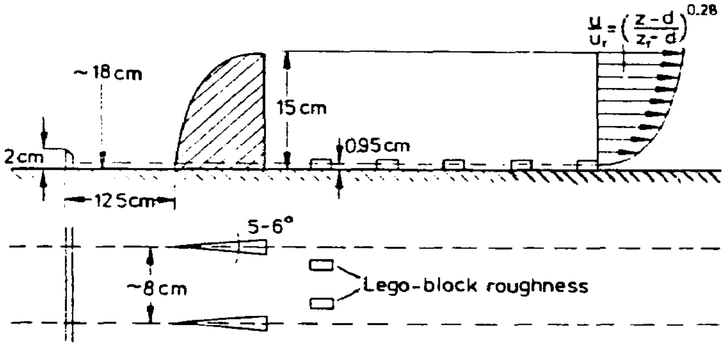
The major practical limitations to accurate wind tunnel simulation of LNG dispersion are operational constraints, particularly the inability (a) to obtain a steady wind profile, or (b) to accurately simulate atmospheric turbulence at the lowest wind speeds of interest, and (c) to maintain the large Reynolds numbers (lower limits as yet somewhat ill-defined) associated with the proper scaling of turbulence, diffusion, and frontal velocities. When combined with estimates of the restraint on plume expansion caused by the tunnel side walls, these considerations permit the preparation of performance envelopes for particular wind tunnel facilities [9,18–21].

3.1 Performance envelopes: land-based spills

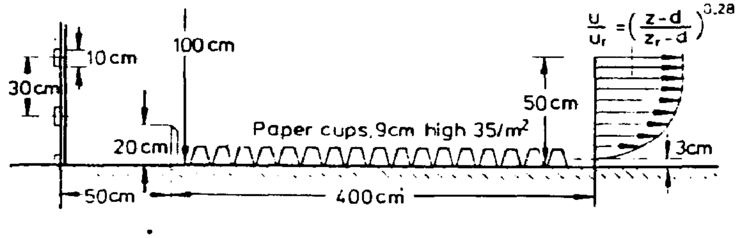
Several alternative performance curves are provided, including sets for undistorted or distorted scaling of density and prototype mean wind speed or



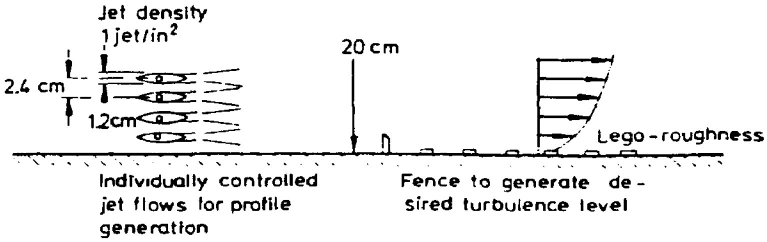
a. Boundary layer generation along test section floor



b. Boundary layer generation with vortex generators



c. Boundary layer generation with fence



d. Boundary layer generation with jets

Fig. 1. Methods for generating boundary layer flows in a wind tunnel [8].

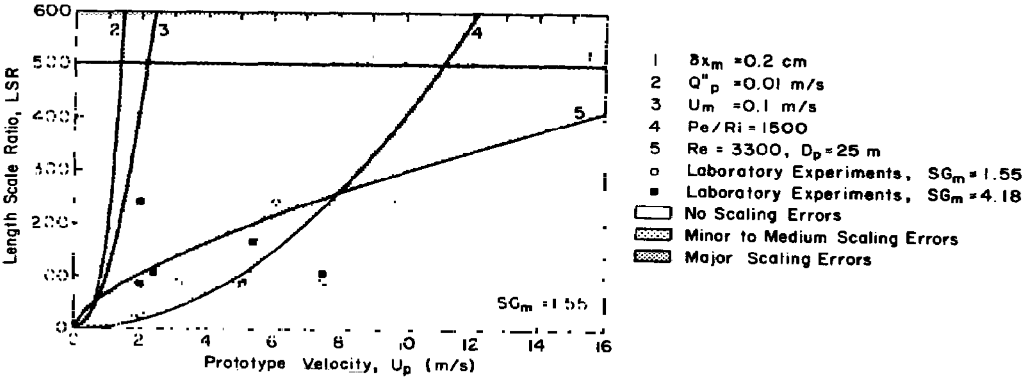


Fig. 2. Performance envelope to simulate LNG spills -- constant boil-off conditions, $SG = 1.5$, tunnel width = 4 m. Length scale ration vs. prorotype wind speed.

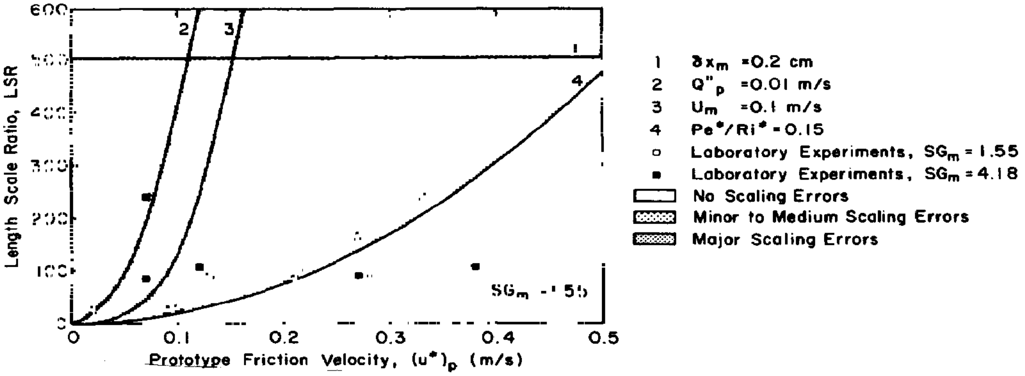


Fig. 3. Performance envelope to simulate LNG spills -- constant boil-off conditions, $SG = 1.5$, tunnel width = 4 m. Length scale ratio vs. prototype friction velocity.

prototype friction velocity. Operational limitations used to construct Figs. 2–5 include:

1. Most large wind tunnels are unable to function satisfactorily at very low wind speeds (< 0.5 m/s). At low wind speeds the wind tunnels become sensitive to small disturbances, both external and internal, which lead to unrealistic perturbation of the mean flow.
2. At low model wind speeds the flow Reynolds numbers fall to low values, and
   a. when the characteristic obstacle Reynolds number falls below 3300, wake turbulence no longer remains similar to field conditions [22]. Figure 2 presumes the prototype obstacle diameter is 25 m.
   b. when the wall roughness Reynolds number falls below 2.5, then the near-wall region may not behave in a fully turbulent manner.

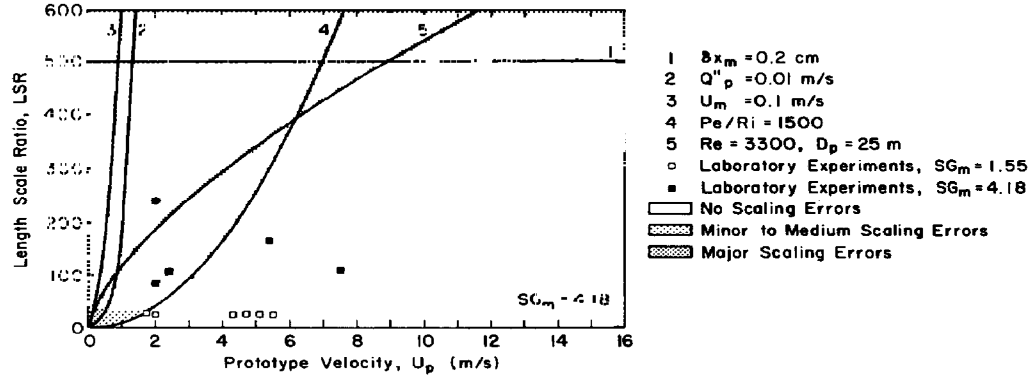


Fig. 4. Performance envelope to simulate LNG spills -- constant boil-off conditions, $SG=4.2$, tunnel width = 4 m. Length scale ratio vs. prototype wind speed.

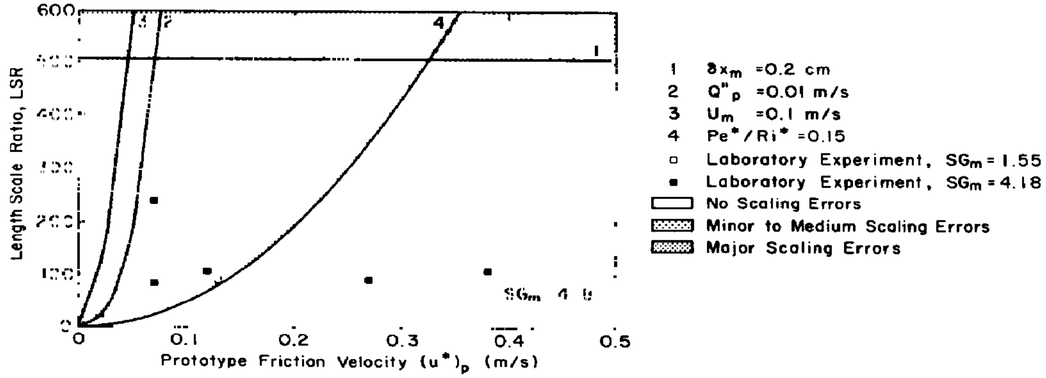


Fig. 5. Performance envelope to simulate LNG spills -- constant boil-off conditions, $SG=4.2$, tunnel width = 4 m. Length scale ratio vs. prototype friction velocity.

3. The minimum spatial resolution for concentration measurements in the laboratory is about 2.5 mm. Minimum pertinent resolution required in the field may be 1 m.

4. Wind-tunnel walls can interfere with lateral spreading of a dense plume. Calculations presume no wall interference before one reaches a distance of 20 diameters downwind of a 0.3 m diameter model source steadily boiling off LNG in a 4 m wide tunnel. Two boil-off rates are possible, 0.01 and 0.1 $m^3/s\ m^2$. The lower value corresponds to typical LNG boil-off rates over soil or concrete, whereas the larger value is typical of boil-off rates over water. The interaction conditions are calculated using the spread formulae proposed by Britter [23].

5. Mixing rates associated with molecular diffusion exaggerate dilution at low wind speeds. Molecular dispersion becomes significant for unobstructed flows when the Peclet/Richardson number ratio, *Pe*/*Ri*, is less than 1500, or

Pe_*/Ri_* is less than 0.2 (Note: This criteria only applies to spill scenarios in the absence of turbulence generated by cloud collapse, tanks, dikes, fences, buildings or water sprays. New experiments are required to define the actual errors associated with falling below $Pe/Ri = 1500$.)

Figure 2 presents guidelines for cases when undistorted density scaling of an LNG spill is intended (i.e., $(SG_g)_m = 1.5$). Note that it is possible to meet roughness and Reynolds number constraints only for very modest scale ratios and high prototype velocities. Indeed most interesting field spills would not fit in conventional facilities if these constraints are retained. Strict observance of the roughness Reynolds number does not seem necessary when self-generated turbulence dominates mixing. Many laboratory tests noted on the figures gave results comparable to field values, even though they disobey this criterion.

Figure 4 presents guidelines for cases when distorted density scaling of an LNG spill is presumed (i.e., $SG_m = 4.2$). In this case, prototype wind speeds less than 2 m/s can be simulated at scales greater than 1:200 without running at tunnel speeds less than 0.2 m/s; however, molecular diffusion will exaggerate dilution for scale ratios greater than 1:100 and prototype wind speeds less than 3 m/s. Obstacle Reynolds number remain above 3300 for 0.3 m diameter model obstacles, even at prototype wind speeds of 1 m/s and scale ratios of 1:200. The filled in data points, ■, are cases where the model source gas specific gravity was equal to 4.2.

Figures 3 and 5 are companion figures in terms of prototype friction velocity.

3.2 Performance envelopes: water-based spills

LNG spills on water differ from their over land counterpart because they:

(a) Boil-off at a maximum rate near 0.1 $m^3/s\ m^2$ as long as LNG remains,

(b) Generally involve larger volumes ($\simeq 25{,}000\ m^3$ of LNG), and

(c) The spill source may have a variable area in time.

Since it is desirable to contain the 5% lateral contour within a test region unaffected by wall reflections, a second set of calculations for performance envelopes were prepared assuming a transient spill configuration. Maximum pool radius after an instantaneous spill is calculated by the equations of Raj and Kalelkar [24]. A modified version of the method of Van Ulden [25] was used to calculate the subsequent gravity spread radius. The gravity spread is assumed to occur until the frontal velocity equals the mean flow velocity; subsequently a 1.5 factor growth in radius is assumed before the 5% LFL condition is reached. Figure 6 presumes a 4 m wide wind tunnel is available.

This figure suggests a 20,000 m^3 LNG spill must be modeled at 1:800 to permit even a 4 m/s prototype wind speed. A 5000 m^3 LNG spill could be contained at scale ratios of 1:600 and prototype wind speeds down to 3 m/s, but laboratory flow speeds would be below 0.2 m/s. Unfortunately such large scale ratios preclude measuring with very good spatial resolution.

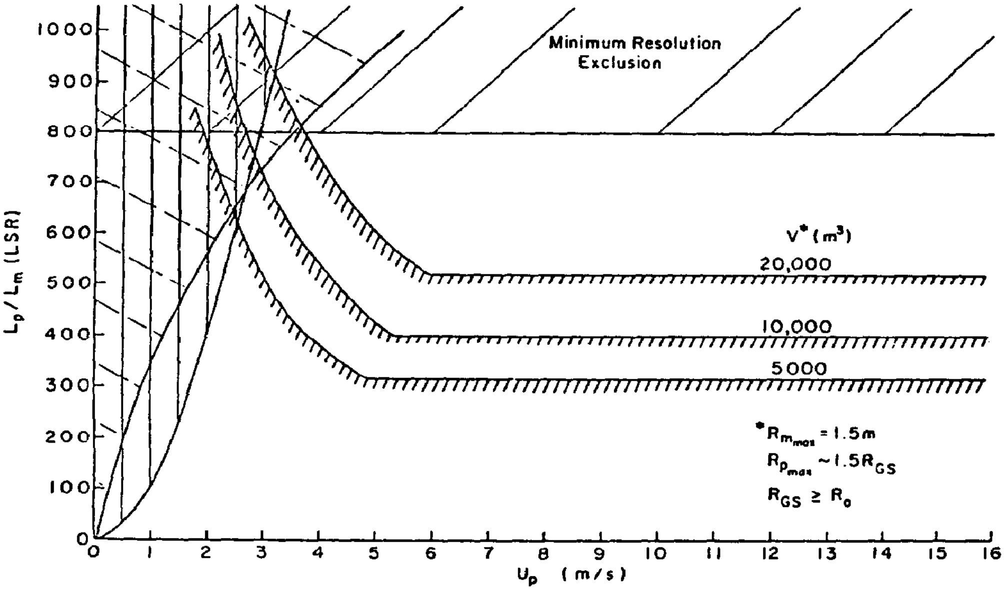


Fig. 6. Performance envelope to simulate LNG spills -- transient boil-off conditions over water, $SG = 1.5$, tunnel width = 4 m. Length scale ratio vs. prototype wind speed. Final radius = $1.5\,R_{GS} > 1.5\,R_o$.

4. Test program for a dense gas fluid model experiment

Those conducting a fluid modeling study and those reviewing the results must share a common set of reference criteria. If all laboratories which conduct physical modeling of dense gas dispersion provide similar setup, wind tunnel calibration, and flow field information, it will provide an opportunity to detect anomalous flows and permit inter-laboratory comparisons of test results.

Different experimental programs will be required, depending upon the purpose of the measurement program. Different sets of measurements are appropriate for basic fluid research, safety design, or meeting regulatory standards. As noted in Section 1 the manner in which the motivating questions are cast will determine the character and details of the measurements required. Nonetheless, some common elements exist in all such measurement programs, and these should be performed in such a manner that the data have maximum value.

A detailed formulation and discussion of the fundamental principles for fluid modeling of dense gas dispersion is provided in Meroney [26]. The necessary model scales, roughness, and flow conditions should be chosen to accommodate earlier arguments. To insure that a stationary, uniform, and homogeneous flow is produced, the following procedures and measurements are recommended:

1. A daily log of the experiment should be maintained recording all normal and abnormal operating conditions encountered.

2. The size of all building structures and the general topography in the vicinity of the spill area should be examined. Upstream sharp-edged buildings and 3-dimensional topography should be included if their height exceeds 1/20th the distance from the source. Two-dimensional obstructions (ridges, fences, etc.) should be included if their height is greater than 1/100th the distance from the source. Topography height should be based on elevation difference between hill peaks and local troughs. For tall thin structures the width is the pertinent scaling dimension. Wind tunnel blockage should be kept below 5% for an ordinary wind tunnel and 10% for a tunnel with a properly adjusted ceiling.

3. Since dense plumes travel directly over the ground surface local irregularities may be important in deflecting or augmenting plume growth. Models should not be terraced. Model roughness should not normally be exaggerated such that it exceeds gas layer depths. Even modest terrain slopes can be important during dense gas dispersion; hence, model terrain should include ground slope if it exceeds 1°.

4. The model should be immersed in an appropriate boundary layer that can be characterized by surface roughness, z_o, friction velocity, u_*, and stability, Ri or L_{mo}. Alternatively, one may specify depth, δ, and velocity power-law coefficient, p.

5. Laboratory wind speeds should be high enough such that obstacle Reynolds numbers exceed 11,000 for sharp-edged objects or 100,000 for rounded objects. Peclet/Richardson number ratios for the simulant gas should exceed 1500.

6. Wind profile and concentration measurements should be made in the wind tunnel in the absence of buildings, large terrain, or other large structures to provide an evaluation of the model flow in absence of such perturbations. Such tests will ensure that no longitudinal or cross-wind aberrations exist in the flow field.

   (a) As appropriate provide vertical profiles of the mean temperature, T (K), and the intensity of temperature fluctuations, T'_{rms}/T, at the spill location.

   (b) Provide vertical profiles of the mean velocity, U (m/s), and the longitudinal and vertical turbulent intensity, u'_{rms}/U and w'_{rms}/U, at the spill position, downwind of the planned study area, and midway between the two positions. Repeat profiles at position midway between the tunnel walls to both the left and right (9 profiles).

   (c) Provide vertical profiles of the shear stress $-\overline{u'w'}$ (m^2/s^2) at the spill position, downwind of the planned study area, and midway between the two positions (3 profiles).

(d) Release dense gas continuously from the spill site at some representative rate. Take vertical and lateral profiles of concentration through the plume centerline at least at the quarter intervals between the source and the end of the planned study area. Take ground-level longitudinal profiles of concentration downwind along the plume centerline to the end of the study area (9 profiles).

(e) Convert model concentrations to equivalent field values. Check at each downwind position of measurement for conservation of mass by estimating Q from the integration

$$Q = \int_{0}^{+l} \int_{-l}^{+l} C(y,z)\,U(z)\,dy\,dz$$

7. Install terrain, buildings and other structures in wind tunnel, and pursue measurement program by measuring comparable profiles of temperature, velocity, concentration, turbulence, and shear as appropriate. At a minimum, measure meteorological variable profiles over spill location.

8. During studies of the transient behavior of instantaneous or finite-time release LNG spills, multiple replications of each spill will be necessary to establish ensemble mean conditions and associated variances. The total number of replications will be determined by the acceptable errors and confidence limits specified; however, it is likely at least 3 to 5 replications of each scenario will be required.

5. Check list for reporting laboratory experiments

Any fluid modeling report should completely document the design and operation of the model study. The facility and any modifications should be described; features of the model should be reported; instrumentation character, manufacturer and model, calibration, and accuracy recorded; behavior of the facility in the absence of model perturbations verified; character of the background simulated meteorological field documented; and, finally, results of the specified experiments tabulated. All too often, one or more of these ingredients are missing, making it very difficult for data users to establish the value of the information.

An archive report should include:

1. Detailed topographical maps of the area studied and discussion concerning the selection of the model area.

2. Description and references to the mode of operation, calibration, sensitivity, and resolution of instrumentation.

3. References to the construction details of the simulation facility, and documentation of any unique modifications to the test section which modify operational characteristics.

4. Documentation for the dispersion comparability test in absence of buildings, structures, large terrain features, or unusual roughness should include:

(a) Detailed description of the fluid model, including features of the scale

model, surface roughness, freestream wind speed, and methods used to provide the simulated boundary layer,
(b) One vertical profile of mean temperature over the spill site,
(c) One vertical profile of temperature fluctuation intensity over the spill site,
(d) Several vertical profiles of mean velocity distributed over the test area,
(e) Several vertical profiles of vertical and longitudinal turbulence intensity at similar locations,
(f) Several vertical profiles of shear stress along the tunnel centerline,
(g) Several vertical and lateral profiles of concentration through the plume center line,
(h) One ground-level longitudinal profile of concentration downwind along the plume center line, and
(i) Evaluation of the effective surface roughness length, z_o, friction velocity, u_*, velocity power law coefficient, p, determined by evaluating the mean velocity profiles and the shear stress profiles.
(Additional valuable information could include velocity spectra, velocity correlations, and integral scales.)

5. Documentation for the experimental situations where the model structure and terrain are in place should include parallel measurements to those taken under Number 4 above.
6. Comparison figures which examine the differences measured during item Numbers 4 and 5 above.

6. Conclusions

Duijm et al. [27] prepared Table 3 comparing potential performance of mathematical and physical modeling based on the present state-of-the-art. Note that fluid modeling does some things better and some things worse than the numerical alternatives examined. McQuaid [3, p. 20] believes at the present time "that the physical model is much more reliable than the 3-D codes." Wheatley and Webber [28, p. II.149] observed that "the complexity and expense of the 3-D models are not yet demonstrably justified by more accurate results".

Wind tunnels are, in effect, analog computers which have the advantage of "near-infinitesimal" resolution and "near-infinite" memory [9]. A fluid modeling study employs "real fluids" not models of fluids; hence, the fluid model is implicitly non-hydrostatic, non-Bosinnesqu, compressible, includes variable fluid properties, non-slip boundary conditions, and dissipation. Real fluids permit flow separation and recirculation. All conservation equations are automatically included in their correct form in a laboratory model without truncation or differencing errors, and there are no missing terms or approximations.

The fluid model bridges the gap between the fluid mechanician's analytic or

TABLE 3

Potential performance of mathematical and physical modelling (Modified from Duijm et al. [27])

Aspect	Box Model	3D-Model[a]	Physical Model
Main model assumption	Rate of entrainment	Turbulence closure assumption	Similarity of full-scale and model-scale flow field
Model results	Averaged concentrations	Averaged concentrations	Visualization (film/video) Averaged and instantaneous concentrations
Spatial resolution	Low	Depends on grid size	Depends on measurement technique
Modelling dispersion over flat terrain	Good	Good	Good
Modeling dispersion over obstacles	Impossible	Possible but difficult	Good
Modelling effects of atmospheric stratification	Fair to good	Fair to good	Possible but requires special facilities
Modelling effects of surface heat transfer	Good	Good	Difficult, requires special equipment. Limited conditions
Modelling effects of ambient humidity	Good	Good	Reasonable over limited conditions
Time needed, initialization of model included	Less than one day	Days to weeks, depends upon terrain complexity	Model making: weeks Separate experiments: minutes to day
Costs	Low	Medium to high	Reasonable in wind tunnel Higher in water tunnel

[a] Presumes problems with grid resolution, gradient transport assumptions, and numerical diffusivity are solved.

numeric models of turbulence and dispersion and their application in the field. One might observe that "If a numerical model cannot predict results of an idealized fluid experiment, what hopes does it have of application to atmospheric scales"?

Finally, "a *well-designed* and *carefully executed* fluid model study will yield valid and useful information — information that can be applied to real environmental problems — with just as much and generally more credibility than *any* current mathematical models" [9].

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List of symbols

C	Calculated or measured concentration
CF	Correction factor for spatial resolution
C_p	Specific heat capacity
D	Source diameter
e	Transducer voltage
f,F	Fluctuating quantity
Fr_a	Froude number, ambient reference density
Fr_f	Flux Froude number
Fr_s	Froude number, source reference density
$g(x)$	Spatial correlation
I_u	Integral scale
K	Transducer voltage response
n	Number of samples
p	Power law coefficient
Pe	Peclet number
Q	Source flow rate
R	Radius
Re	Reynolds number
Re_{Da}	Source Reynolds number, ambient reference
Re_{Ds}	Source Reynolds number, source reference
Ri	Richardson number
Ri_b	Bulk Richardson number
Ri_*	Richardson number, friction velocity
Ri_f	Flux Richardson number
SG,sg	Specific gravity
t,T	Time
T	Temperature
u,U	Velocity
u,v,w	Velocity components
u_*	Friction velocity
V	Volume
W	Source gas exhaust velocity
x,y,z	Cartessian coordinates
z_o	Roughness length

Greek symbols

β	Terrain slope
λ_T	Taylor microscale
σ	Variance
o	Transducer sample size

Superscript symbols

——	Average
$'$	Fluctuating component

Subscript symbols

a	Ambient atmospheric conditions
g,o	Source gas
m	Model
p	Prototype
R	Reference

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