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Project Officer
Ronald K. Patterson

Prepared by

Research and Evaluation Associates, Inc.

1030 15th Street, N.W., Suite 750
Washington, D.C. 20005
(202) 842-2200

100 Europa Drive, Suite 590
Chapel Hill, N.C. 27514
(919) 968-4961

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LAB-SCALE EXPERIMENTS

Robert N. Meroney

Fluid Mechanics and Wind Engineering
Civil Engineering Department
Colorado State University
Fort Collins, CO

As a physical modeler in a room full of numerical modelers, I must confess I feel like a chicken in a fox house. So, I will do the best I can, and you must decide whether or not you are convinced. I want to talk about the capabilities of physical fluid modeling with respect to meeting the needs of the hazardous materials community. There are many experiments that can be classified as basic fluid mechanics experiments associated with the mixing process. There are tests that have been performed for the meteorological community associated with pre-field test planning experiments. There are concept testing experiments where, for example, a certain mitigation device can be tested for feasibility. There are validation experiments that can be performed specifically to determine whether physical modeling can provide a viable approach to solving some particular problem. Finally, there are experiments that have been directly applied to hazard analysis. The goals of all of these experiments is to test, calibrate, and validate a numerical code.

One might note that if a code is not capable of predicting the behavior of an idealized laboratory-controlled experiment, one should not feel the right or the ability exists to predict a far more chaotic field experiment. As a proponent, I will say a couple of words about the advantages of fluid modeling. Wind/water facilities are in effect analog computers, and they have special attributes. They have near-infinitesimal resolution. Grid sizes are not a concern. The transport processes, one could argue, go down to the molecular level. The facilities have near infinite memory. They also have the ability to look at very large three-dimensional grid regions. Fluid modeling incorporates real fluids, not models of fluids. We, therefore, start out using the right stuff in the right place, not someone's concept of how the atmosphere or fluid behaves. Implicitly, this analog computer is nonhydrostatic, non-Bosinnesque, capable of compressible effects, thermal effects, and includes variable property. It includes a non-slip boundary condition, effects of dissipation, and many nonlinear processes. Also, it inherently includes full conservation equations without truncation.

On the down side, there are some limitations. At smaller scales, one must recognize that some similarity is lost in the mixing processes. As speeds drop to handle stratified fluids, the Reynolds numbers decrease, and it is possible that the Reynolds number can drop below some critical value in different phases of the mixing process. Depending on the phenomena, this may result in a minor or a major error. When running experiments at very low speeds, one reaches a point, perhaps associated with the fluid number dominance, where the ratio described as the Peclet number over the Richardson number first proposed by Colenbrander and Puttock from Shell Research, Ltd., is less than some critical value. This means, basically, that you are operating at such a low rate of mixing that the molecular mixing exceeds the scaled turbulent mixing. This is the only phenomenon that tends to give a nonconservative result in physical modeling. Almost all other errors tend to give conservative results.

As smaller scales are used in the laboratory, the separation we are familiar with in the atmosphere between the integral scales, Taylor scales, and Kolmogorof scales of turbulence, will bunch up. Depending on the kind of mixing process under study, this may or may not be important.

There are a number of basic fluid mechanics experiments one might wish to consider. Anyone who has produced a numerical model that uses an entrainment rate at a box-model or a slab-model level or who has worked with various K-theory-type models has probably drawn from physical modeling for basic turbulence coefficients. Some of the earliest work by Lofquist, associated with overflow of fresh water over saltwater, generated the information we use today on the entrainment variation of Richardson numbers. Basic experiments by Kantha, where a surface plate was dragged around and around on top of a circular channel filled with stratified salt water, the merry-go-round experiments, have provided us with additional information. Some errors were later found in these experiments, and meteorologists did experiments to improve this work (Willis and Deardorff and, later, Lindberg). In England, McQuaid has done some basic experiments on transport through dense shear layers associated with carbon dioxide (CO_2) releases. Jerry Havens and I also have done some basic experiments.

We should consider some simple idealized cases. Yang, a student of mine in 1972, and I did some laboratory puff model experiments, where we released thousands of puffs of gas in a boundary layer shear flow and were able to develop models for a transport similarity that included probability density distribution and various coefficients associated with lateral, vertical, and longitudinal variation. These models and the coefficients very closely agree with models we are using today. In 1980-81, Lohmeyer and I did some experiments with instantaneous volumes of dense gases, releasing them at the wall of the boundary layer. At that time, there were no field experiments to guide us, but we identified the basic characteristics of the dense gas cloud. The behavior of the arrival time, the departure time, and the statistical deviations within a multiple sum average condition of a torus-shaped cloud, I believe, are very important. These are critical points for issues of flammability and toxicity. We cannot make decisions based on average conditions, but must know about the statistical range of conditions that exist. A gas cloud is not set on fire by the average conditions that exist. It is the instantaneous concentration that sets the fire.

There have been several somewhat complex studies done in the laboratory, including both dense gas cloud effects and heat transfer effects. The best known of these is the tank experiments on the convective boundary layer concept by Willis and Deardorff. These were heated water experiments that have had a revolutionary effect on both numerical modeling and our field understanding of the convective boundary layer. One of the key points from these experiments is that we now know that clouds released through plumes at the ground tend, in a short distance in a convective boundary layer, to rise. Also, clouds released at elevated points in the convective boundary layer can fall. Maybe on average this point is not so important, but it can make a very big difference in how you should be calculating the results of a toxic or flammable cloud passage.

What kind of pre-field planning experiments are possible? We have performed pre-field tests studying the effects of field terrain, windward variation, and stability. We have looked at instrument placement and cloud extent.

Post-field test experiments also can be useful. Recently in some DOE and Gas Research Institute-funded work preceding the 1987 LGF vapor barrier tests, we found some unexpected things occurred. In the vapor barrier-contained region, we found that the gases sloshed up against the end, hit the barriers like a wave, were caught in the air flow passing over the barriers, and were transported downwind at fair heights. Thus, we found bursts of higher concentrations at higher elevations than were observed in the numerical experiments.

Physical fluid modeling also can play a very useful role in testing of concepts. When the gas industry was looking at alternative secondary containment schemes for large tank storage, there were questions about berm heights for large volumes of cryogenic chemicals. There were questions also about whether soil surfaces or insulated concrete surfaces were better inside the berms and about the comparative effects of these choices on the eventual dispersion of resulting gases. With physical fluid modeling, we were able to test many options and learn not only the answer to those questions, but at that time due to the early nature of those experiments (mid 1970s), we were able to learn new fluid flow fundamentals as well.

In some work with Factory Mutual, funded by the Gas Research Institute (GRI), we looked at water spray curtains and how they mitigate cloud dispersion. In this case, simultaneous field tests were run that were very confusing due to the unexpected results that occurred. Our work on nozzle sizes, varying water pressure, and wind speeds helped to explain the nature and extent of mitigation that did occur in these experiments.

As mentioned earlier, idealized experiments have been used extensively to calibrate modules of various models. Some numerical models have been calibrated against both laboratory and field results. Physical fluid modeling can serve as a useful method for evaluating Federal regulatory-specified accident scenarios at existing or planned facilities. For example, we were able to model such a scenario, a guillotine of a pipeline with 10 minutes of spill at the maximum flow rate, for the Brooklyn Union gas storage facility on Long Island. The experiment showed a positive result, that no effects would be seen beyond the facility boundary in the event of that accident. Since there were resources remaining in the contract, they had us look at larger, even less likely potential accidents, such as spilling the entire tank. This time the results were potentially far more catastrophic, even though unlikely.

Wind tunnel measurements can be very helpful during risk assessment, licensing, or the regulatory process. DOT regulations currently require the use of an extremely over-conservative numerical algorithm. The model does not account for roughness, obstacles, terrain, or mitigation devices. To prepare for licensing hearings for a liquefied natural gas (LNG) peak-shaving facility on Staten Island, we examined spills at about a 1:250 scale model. We introduced conservatism into the experiment by simulating larger, heavier spills in an environment with reduced mixing. The facility appeared to meet DOT requirements even when significantly more extreme conditions were considered than required by DOT regulations.

Recently, field/laboratory validation experiments have been completed for both instantaneous and continuous releases of dense and cryogenic gases. In work for the GRI (Meroney, 1986), I examined some 26 field/laboratory data sets and found that the laboratory-predicted distances to lower flammability limit (LFL) on the average to within 0.4 percent of actual values with a standard deviation of ± 22 percent. Pattern comparison plots of concentration isopleths could always be matched by appropriate fluid modeling techniques with less than a 15^{o} shift in surface patterns. The British Maritime Technology group in the United Kingdom scaled the recent Thorney Island field spills of Freon^{TM}-air mixtures. They found no apparent lower limit for Reynolds number or Peclet/Richardson number-scaling criteria for collapsing dense clouds.

It is now apparent that fluid modeling can faithfully reproduce the physics of transient dense gas cloud entrainment and motions within the inherent variability of the process for many interesting situations. Fluid modeling can contribute valuable input information for future siting and risk analysis models for the chemical and petroleum industries.

REFERENCE*

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*Author's/Editor's Note: All of the work by other researchers mentioned in this presentation are referenced in the above citation.