DEVELOPMENT OF A HIGH-PRESSURE WATER TUNNEL FACILITY FOR OCEAN CO_2 STORAGE EXPERIMENTATION

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INTRODUCTION

The rising atmospheric levels of greenhouse gases, primarily CO_2, due to the production and use of energy is a topic of global concern. Stabilization may require measures other than fuel switching to lower carbon energy sources, increased use of renewable energy, and improvements in efficiencies. A new way of potentially limiting atmospheric increases of CO_2 while maintaining energy diversity is carbon sequestration which entails the capture and non-atmospheric storage of the carbon emitted from energy production and use. A recent report describes the key areas of research and development presently viewed as necessary to understand the potential of carbon sequestration for managing carbon emissions (1).

One potential storage option is to directly introduce CO_2 into the ocean at depths greater than about 500 m (1,2). Part of the carbon sequestration research program at the National Energy Technology Laboratory (NETL) of the U.S. Department of Energy has involved work in this area (3,4). This work has focused primarily on the impact on this storage option of the possible formation of the icelike CO_2 clathrate hydrate ($CO_2 \cdot nH_2O$; $6<n<8$; referred to hereafter simply as hydrate) as either discreet particles or as coatings on drops of liquid CO_2. All of this prior work was performed in a small (less than 40 cm^3) pressure vessel. While useful data on the formation, dissolution, and relative density of the hydrate were obtained, realistic simulation of the oceanic environment was not possible owing to contact of the species of interest with foreign (glass, stainless steel) materials in such a vessel. These foreign materials can influence hydrate formation and dissolution by acting as nucleation sites and providing unnatural heat transfer characteristics, both important factors in crystallization processes.

To attempt to overcome these limitations and provide a more realistic simulation of the deep ocean environment, a High-Pressure Water Tunnel Facility (HWTF) is being constructed that will permit experimental observations on objects such as CO_2 drops, hydrate particles or hydrate-covered CO_2 drops to be made without contact with materials other than seawater. The HWTF will permit the observation of buoyant objects in a windowed test section through the use of a countercurrent flow of water and special design features that provide for radial and axial stabilization. This paper describes the status of the experimental and theoretical efforts associated with the development of the HWTF.

DISCUSSION

In 1981, Maini and Bishnoi published work on the development of a high-pressure water tunnel to study hydrate formation on freely suspended natural gas bubbles in a simulated deep ocean environment (5). Their design considerations formed a starting point for the work at NETL on ocean sequestration of CO_2. As summarized in their paper, the hydrodynamic conditions necessary for holding an object in free suspension in such a device consist of: 1) the drag on the object should be equal to the force of buoyancy; 2) the axial velocity of the liquid should gradually increase with height to provide stability against vertical displacement; 3) the velocity distribution over a cross section of the liquid column should be axially symmetric with a local minimum at the center to provide stability against lateral displacement; and 4) the flow should be free of large-scale turbulence. To achieve the desired velocity profiles, an observation section with a tapered inner diameter and various flow conditioning devices inserted above and possibly below this section can be used.

A simplified schematic drawing of a water tunnel device is shown in Figure 1 (only inner diameters are shown). This device is placed in a flow loop that provides for recirculation of water through the system. For a positively buoyant object, the flow of water or seawater enters the top of the water tunnel and passes through a stilling section (not shown in Figure 1). At the end of the stilling section, a flow conditioning element is placed to provide the velocity profile required for radial stabilization of the buoyant object in the test section immediately below it.

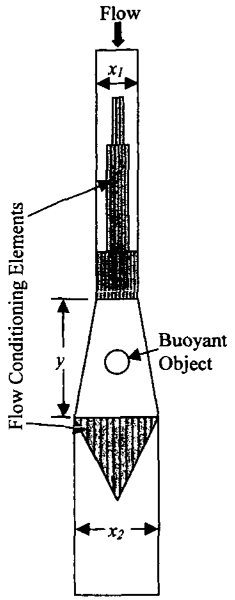

Figure 1. Schematic diagram of a water tunnel device

The top flow conditioning element shown in Figure 1 represents a bundle of small tubes of different length. Various other configurations are possible. Increasing the length of the tubes in the center results in more head loss in this region and results in flow redistribution with the desired local velocity minimum in the center of the water tunnel. The diameter of the test section increases from top to bottom ($x_2 > x_1$) which provides the downstream axial velocity drop required for axial stabilization. At the exit of the test section, another flow conditioning element may be used. In Figure 1, this lower element depicts another possible tube bundle shape that could be used. A final stilling section is located after the test section (again not shown in Figure 1). Design variables affecting the velocity profile in the test section include the geometries of the conditioning elements and the divergent test section.

Both experimental and theoretical work is in progress at NETL to determine the required design parameters needed for stabilization of CO_2 in a HWTF over the range of anticipated ocean injection conditions. A Low-Pressure Water Tunnel Facility (LWTF) of similar internal dimensions (x_1 = 5.08 cm, x_2 = 6.35cm) has been built to test various designs and provide information for the theoretical treatment of this problem. It consists of the water tunnel which is constructed of plexiglass pipe, a 5.08 cm ID flow loop of PVC plastic pipe, and a variable-speed centrifugal pump for water circulation. An ultrasonic flow sensing system is used to measure the total flow rate in the loop. An S-shaped pitot tube was fabricated and calibrated at NETL for insertion through ports in the test section and is automatically moved across the section's diameter to obtain information related to local velocities. A computer-controlled positioning system translates the pitot tube across the test section and obtains the measurements needed to determine a velocity profile at this point in the system.

An example of velocity profile data obtained in this manner over a range of flow rates is shown in Figure 2. Only an upstream flow conditioning element similar to the top one in Figure 1 was used to create the velocity profiles shown in Figure 2.

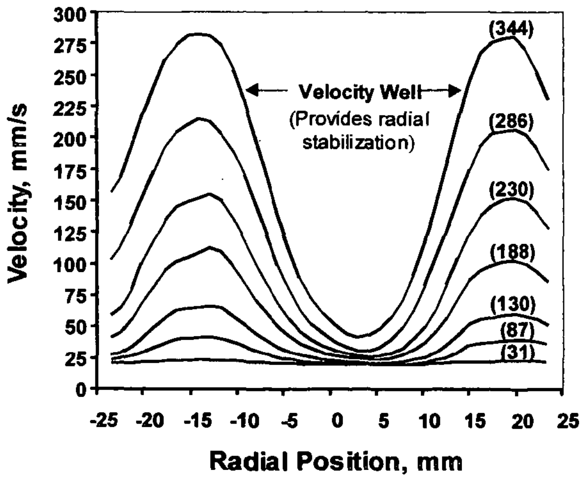

Figure 2. Velocity profiles obtained in LWTF test section using a pitot tube inserted 7.5 cm below the flow conditioning element. Each curve was obtained at a different total flow rate (average flow in cm^3/s shown in parentheses). Radial position is measured from the center of the test section.

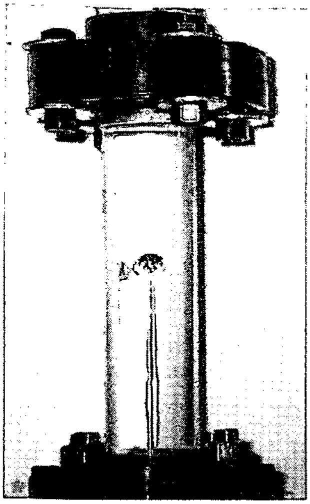

Figure 3. Air bubble stabilized in the test section of the LWTF.

Figure 3 shows an air bubble stabilized in the test section of the LWTF. Similar stability was also achieved using plastic spheres of varying size and density. A single flow conditioning element similar to the one shown in Figure 1 at the top of the test section was used. It consisted of a tube bundle containing longer tubes in the center.

In previous work (5,6), different types of flow conditioning elements were used; however no systematic analyses were performed to relate possible configurations of the flow conditioning elements to the velocity profile and the resulting positional stability of the buoyant object. Presently, in the work at NETL, theoretical optimization of flow conditioning element configuration is being pursued. This work is divided into two steps:

1. Given the mass and density of the bubble or drop (hereafter referred to as fluid particle), determine the optimal velocity profile to stabilize the position of the fluid particle;

2. Given the optimal velocity profile, find the geometry of the flow conditioning element(s) which not only produce such a profile, but also minimize degeneration of it through the test section.

The optimum velocity profile for fluid particle stabilization is expected to vary with the regime of flow. Prior work by various researchers on bubbles and on rising and falling drops in different fluids reveals a variety of regimes, the realization of which depends on a small number of non-dimensional parameters. A non-dimensional analysis is therefore necessary to determine the relevant independent parameters for the anticipated regimes in a water tunnel device.

If a uniform flow of an incompressible fluid past the fluid particle is considered and if the effects of the wall and flow inside the fluid particle are ignored, then there are six parameters of interest, which are summarized below in Table 1.

Table 1. Parameters of Interest for Flow Analysis

Variable	Definition	Dimensions (MLT)
D_e	Effective Diameter	L
U	Free Stream Velocity	L/T
ρ_l	Liquid Density (water)	M/L^3
$\Delta\rho$	Density Differential ($\rho_l - \rho_g$)	M/L^3
μ_l	Viscosity of Liquid	M/(LT)
γ	Surface Tension	M/T^2

There are three primary dimensions for the six physical and geometric parameters: mass, length, and time (MLT). From the Buckingham Pi Theorem, it follows that there will be three independent dimensionless numbers for this system. The choice of these dimensionless parameters is not unique, which means there is some freedom to choose parameters which are the most suitable for this analysis.

It is helpful to relate the definitions of the dimensionless numbers to characteristic values of the effective forces acting on the fluid particle. Four considered effective forces are shown below in Table 2.

Table 2. Effective Forces Acting on a Fluid Particle

Effective Forces	Characteristic Magnitudes
Viscous Forces	$\mu_l U D_e$
Buoyancy Forces	$\Delta\rho\, g\, D_e^3$
Surface Tension Forces	γD_e
Inertial Effects	$\rho_l U^2 D_e^2$

Displayed in Table 3 are the definitions of commonly used dimensionless numbers for bubbles in uniform flow. Various triplets of these dimensionless numbers are used in the literature (7,8):

Table 3. Dimensionless Variables for Flow Analysis

Non-dim. Variable	Name	Ratio of Physical Phenomena	Definition
Re	Reynolds Number	Inertial/viscous	$\rho_l U D_e / \mu_l$
Ca	Capillary Number	Viscous/surface tension	$\mu_l U / \gamma$
Eo	Eotvos Number	Buoyancy/surface tension	$(\Delta\rho g D_e^2) / \gamma$
We	Weber Number	Inertial/surface tension	$(\rho_l U^2 D_e) / \gamma$
Wg	Inertial Buoyancy Parameter	Inertial/buoyancy	$(\rho_l U^2)/(\Delta\rho g D_e)$
Cg	Viscous Buoyancy Parameter	Viscous/buoyancy	$(\mu_l U)/(\Delta\rho g D_e^2)$
Mo	Morton Number		$(\Delta\rho g \mu_l^4) / (\rho_l \gamma^3)$

Reference 7 considers shape regimes for fluid particles as a function of Re and Eo numbers. There exist two limiting cases where the analysis can be significantly simplified:

Case 1. Small Re and Eo numbers, under which the fluid particle has an almost spherical shape. Often, this regime is realized for very small particles (<0.5mm in diameter), or for the slow motion of the fluid particle caused by a very small buoyant force (small difference in density). In this case the terminal velocity of the fluid particle can be expressed (9,10) as:

$$U_{term} = \frac{1}{K} \frac{D_e^2 g \Delta\rho}{\mu_l} \quad (1)$$

(constant K spans from 12 to 36 in different theories and is believed to depend on surface active impurities in the liquid).

Case 2. Large Re and Eo numbers, under which the fluid particle has a spherical cap shape with a well determined front boundary and an unstable, wavy rear boundary caused by the wake behind the fluid particle. Often, this regime is realized for large bubbles (> 2 cm^3 volume), when inertial effects dominate viscous effects and surface tension. Then, the terminal velocity of the fluid particle can be expressed (7) as:

$$U_{term} = \frac{2}{3} \sqrt{gR \frac{\Delta\rho}{\rho_l}} \quad (2)$$

where R is radius of curvature of the fluid particle at the stagnation point.

For intermediate values of Re and Eo, different kinds of transitional regimes occur which are essentially unstable. Therefore, it would be beneficial to design experiments corresponding to one of the limiting cases outlined above.

The liquid CO_2 particle/seawater system is expected to exhibit Case 1 behavior since the densities of seawater and CO_2 are not that different under anticipated direct ocean injection conditions. Owing to its greater compressibility, at depths greater than about 2700 m, liquid CO_2 can even be more dense that seawater. Sphericity of the fluid particle can significantly simplify both the theoretical analysis and experimental observations. Past experimental works show that for a small Re number, fluid particles of almost spherical shape exhibit a rectilinear motion. As the Reynolds number is increased, the wake behind the particle begins to oscillate and further increases in Reynolds number lead to periodic shedding of the vortices (9). Absence of lateral oscillations and significant wakes behind the fluid particle at low Reynolds numbers makes this regime very attractive for initial experiments involving hydrate formation. Hence, it would be useful to determine the optimum size of the fluid particle, small enough to be in the spherical regime, but big enough for meaningful observations. Preliminary non-dimensional analysis shows that at the depths of about 2400-3000 m, a CO_2 fluid particle of 1-cm diameter should be close to spherical. When the optimum size of the fluid particle is determined, optimum flow conditioning elements for this particular size can be developed.

The HWTF has been designed to permit investigation of other species, such as other flue gas components (N_2, O_2, SO_2) and natural gas components, which may have properties quite different than those of CO_2. In these cases, behavior more like Case 2 may be encountered. The modeling work will eventually be extended to develop flow conditioning elements for such systems.

In conjunction with the measurements being made using the LWTF, a preliminary simplified analytical evaluation of the flow conditioning system used in LWTF has been completed. This evaluation provides an approximation for the velocity distribution immediately downstream of the flow conditioner due to different resistances across the tube bundle system. Having a data base of different profiles corresponding to different flow conditioners will permit the appropriate design of the flow conditioner to be selected to meet the desirable velocity profile for fluid particle stabilization. It will then be used to guide the design of the flow conditioning elements for the HWTF.

In order to avoid the assumptions inherent in the simplified analytical evaluation, full three-dimensional finite element analysis (FEA) of the flow through the conditioning element will be performed. This numerical approach enables both a more accurate model of the actual element geometry and the exploration of the velocity profile degeneration downstream of the conditioning element.

The numerical domain will include a straight section upstream of the spoiler, the spoiler system, and the diverging/converging test section downstream of the spoiler. The straight upstream section is included since the velocity profile immediately upstream of the flow conditioning element is not known a priori. This length of the upstream section is made long enough to approximate fully developed inlet conditions. If necessary, the actual inlet geometry of the experimental device can be included. From this three dimensional analysis, velocity profiles throughout the test chamber can be obtained.

The theoretical analyses described above is a sizeable analytical and numerical challenge. This work is not only necessary for the design optimization of the flow conditioning elements and internal geometry of the HWTF for CO_2 ocean sequestration research, but will also be useful in utilizing the device in applications involving different fluids.

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REFERENCES

1. *Carbon Sequestration Research and Development*, U.S. Department of Energy Report, DOE/SC/FE-1, 1999, available NTIS.
2. Herzog, H. *Greenhouse Gas Control Technologies*, B. Eliasson, P.W.F. Riemer, and A. Wokaun, eds., Pergamon, Amsterdam, 1999, 237-242.
3. Warzinski, R.P., G.D. Holder *Ibid*, 1061-1063.
4. Warzinski, R.P., R. J. Lynn, G.D. Holder *Third International Conference on Gas Hydrates, Annals of the New York Academy of Sciences*, in press, 1999.
5. Maini, B.B. & P.R. Bishnoi *Chem. Engng. Science* **36**, 1981, 183-189.
6. Moo-Young, M., G. Fulford, I. Cheyne. *Ind. Eng. Chem. Fundam.*, **10**(1), 1971, 157-160.
7. Clift, R., J. R. Grace, M. E. Weber. *Bubbles, Drops, and Particles*, Academic Press, 1978.
8. Leal, L.G. *Computational Studies of Drop and Bubble Dynamics in a Viscous Fluid*, Drops and Bubbles, Third International Colloquium, 1988, 147-168.
9. Batchelor, G.K. *An Introduction to Fluid Dynamics*, Cambridge Univ. Press, 1967.
10. L.-S. Fan, K. Tsuchiya, *Bubble wake Dynamics in Liquids and Liquid-Solid Suspensions* (Butterworth – Heinemann), 1990.