## IOWA STATE UNIVERSITY

The report from Iowa State University for the period follows.

# CFD INVESTIGATION OF SLURRY BUBBLE COLUMN HYDRODYNAMICS

## Fifth Quarterly Report

**Budget Year 2 – 5th Quarter**
**For**
**January 1 – March 31, 2001**

### Highlights

- Used CFDLIB to simulate conditions described in Zenit et al. (J. Fluid Mech., vol. 420, pp. 1-36, 2000) to validate simulation result.
- Determined that small column diameters cannot be accurately represented by periodic boundary conditions.
- Studied free-slip boundary conditions versus periodic boundary conditions to determine whether or not free-slip boundary conditions could be a suitable alternative.

## 3D Bubble Column Results

During this quarter, work at Iowa State University continued using the 3D version of CFDLIB to simulate flow within air-water bubble columns.

Jyoti Singh has used CFDLIB to simulate the column described in the paper by Zenit et al. (J. Fluid Mech., vol. 420, pp. 1-36, 2000). This experiment uses a column that is 2 m high, and bubbles are produced uniformly from a 2-cm by 20-cm capillary array at the bottom of the column. These dimensions allow one to assume nearly 2D flow within the center of the column. Consistent with the experimental measurements, bubbles are assumed to be almost spherical and 1-2 mm in diameter.

Simulations were first performed using a domain size equal to that described by Zenit et al. (J. Fluid Mech., vol. 420, pp. 1-36, 2000), with a grid spacing of (width) 1 cm by (height) 0.4 cm by (depth) 1 cm. Air was introduced uniformly at 2 cm/s. These CFDLIB simulations illustrated that air predominantly rises through the center of the column, as shown in Figure 1. This was in disagreement with the results described by Zenit et al. (2000), in which air is uniformly distributed within the column. Simulations resulted in an average air volume fraction of 7 percent at 25 seconds, a value lower than that found experimentally (10 percent). Figures 2-4 show the water velocity profiles at 25 seconds. Note that due to the small number of grid cells in the z direction (2), W1 shown in Figure 4 is not fully resolved.

In order to improve the resolution, another set of simulations was then performed under the same conditions. However, a smaller grid size was used, with 0.5-cm cells along the column height, 0.5 cm along the column width, and 0.25 cm along the column depth. These simulations resulted in an average air volume fraction of 10.15 percent after 10 seconds of simulation time. This value was much closer to the experimental value of 10 percent measured with an impedance probe, and 11 percent measured with a gas flow meter.

The results of the 3D “high-resolution” simulations are very encouraging. We will continue to collect simulation data at various air superficial velocities for comparison with experimental data. Our long-term goal will be to use these data to develop a multiphase turbulence model that is computationally more efficient than the “high-resolution” simulations.

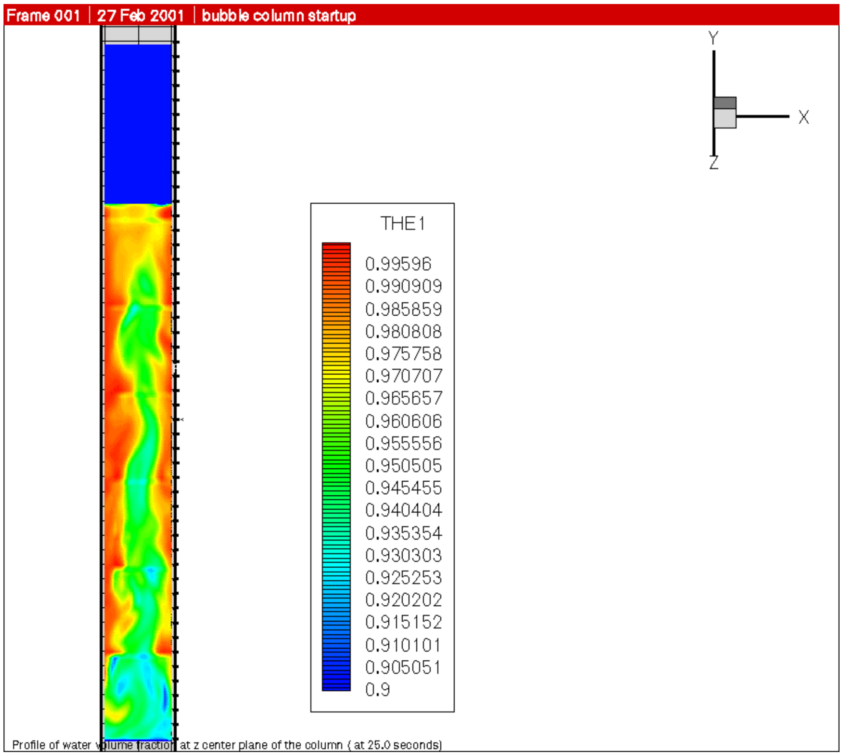

**Figure 1 Profile of Water Volume Fraction at Z-Center Plane of the Column at 25 seconds (blue color represents values 0.0-0.9)**

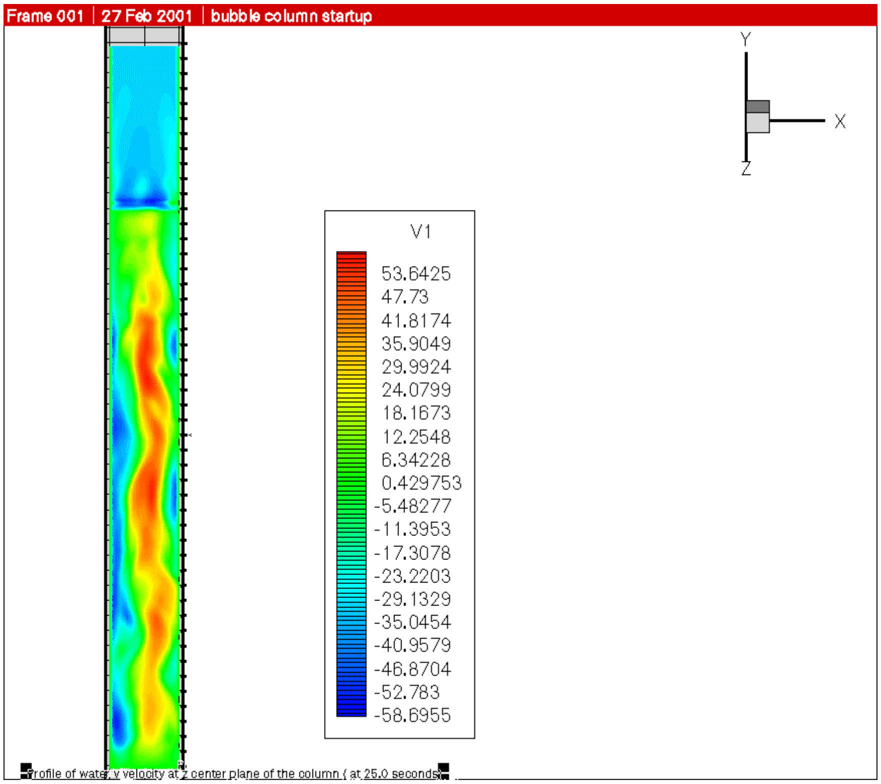

**Figure 2 Profile of Water Velocity in the Y-Direction at the Z-Center Plane of the Column at 25 seconds**

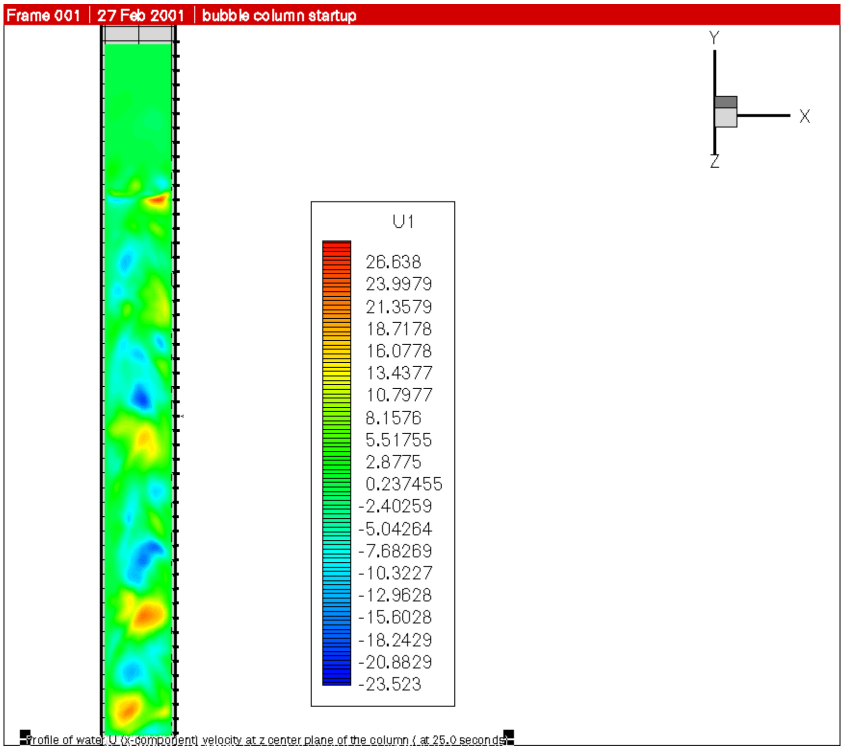

**Figure 3** Profile of Water Velocity in the X-Direction at the Z-Center Plane of the Column at 25 seconds

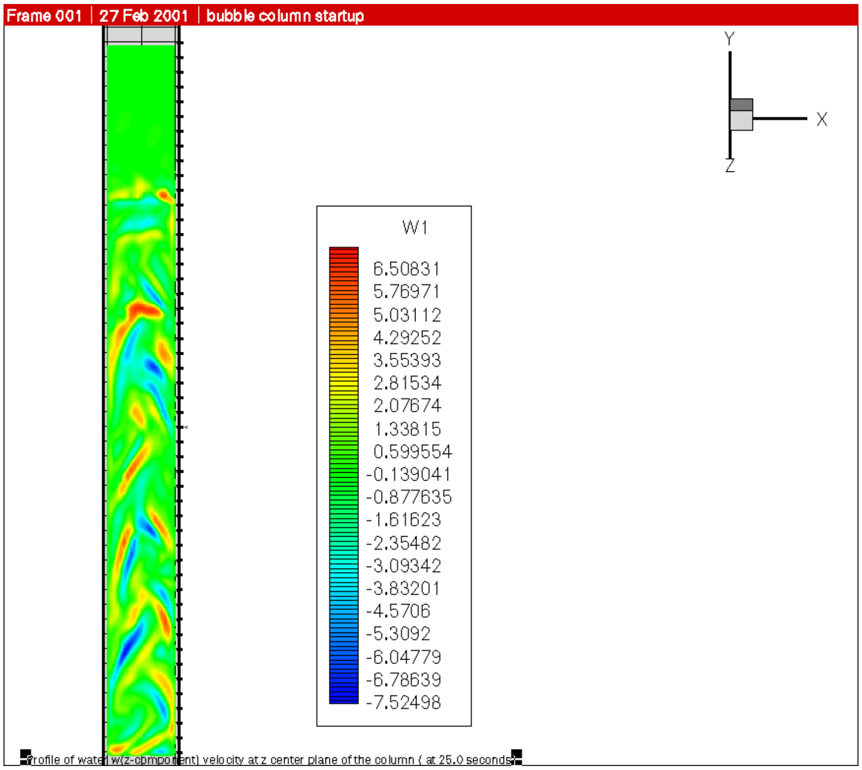

**Figure 4** Profile of Water Velocity in the Z-Direction at the Z-Center Plane of the Column at 25 seconds

## Effect of Boundary Conditions

Sarah Monahan has been using CFDLIB for 3D simulations utilizing periodic boundary conditions. The use of periodic boundary conditions allows one to neglect effects at the column walls. Simulations first used dimensions of 200 cm in height, 20 cm in width, and 2 cm in depth, the same dimensions used in the paper by Zenit et al. (J. Fluid Mech., vol. 420, pp. 1-36, 2000). Air bubbles were assumed to be spherical, with a diameter of 1.5 mm, and were introduced uniformly to the column at 2 cm/s. Cubic grids of both 1 and 0.5 cm were studied. The finer grid size generated a more detailed representation of the air volume fraction within the column. An example of this is illustrated in Figures 5 and 6.

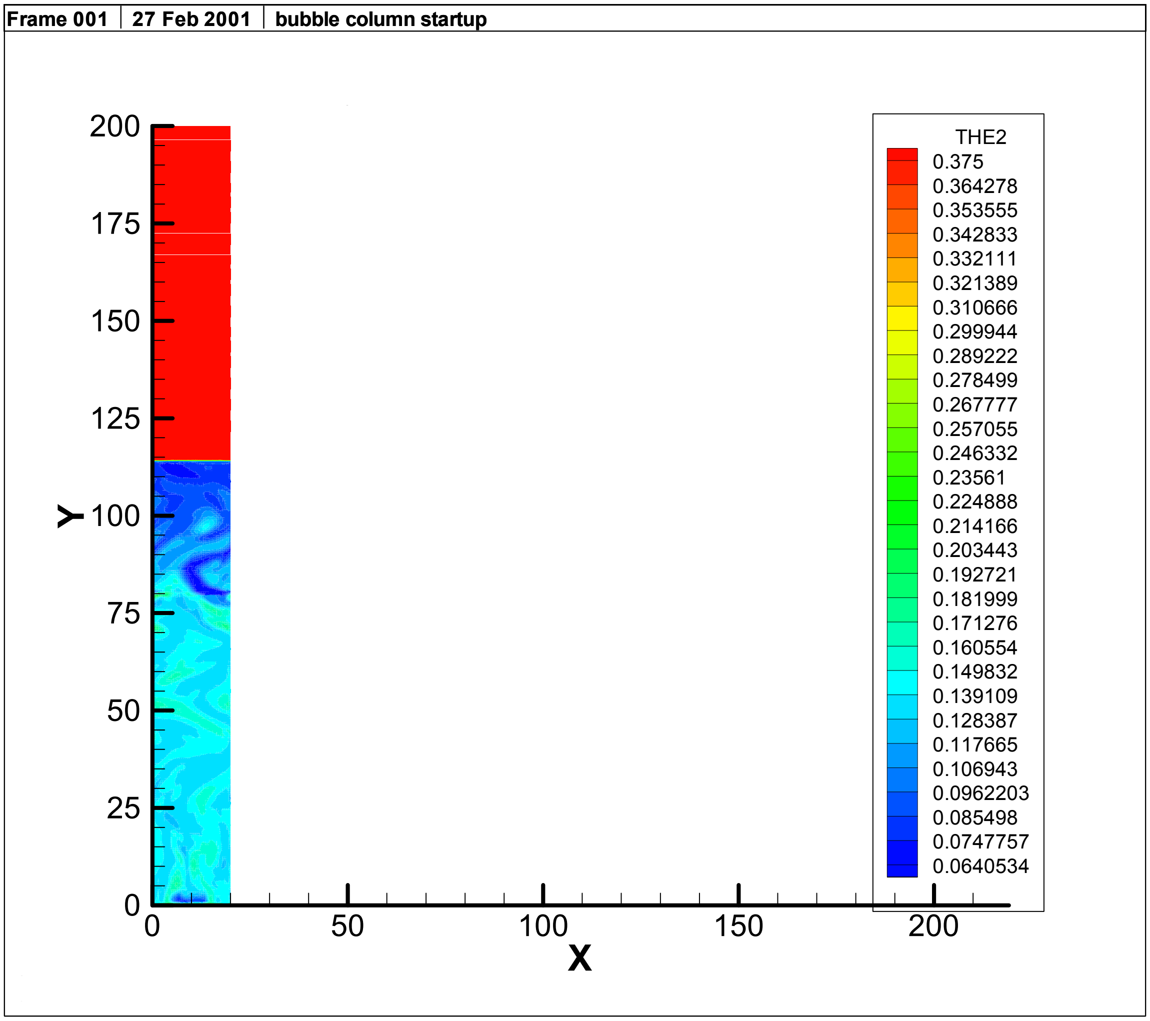

**Figure 5 Volume Fraction of Air for the 0.5-cm Grid Simulation**

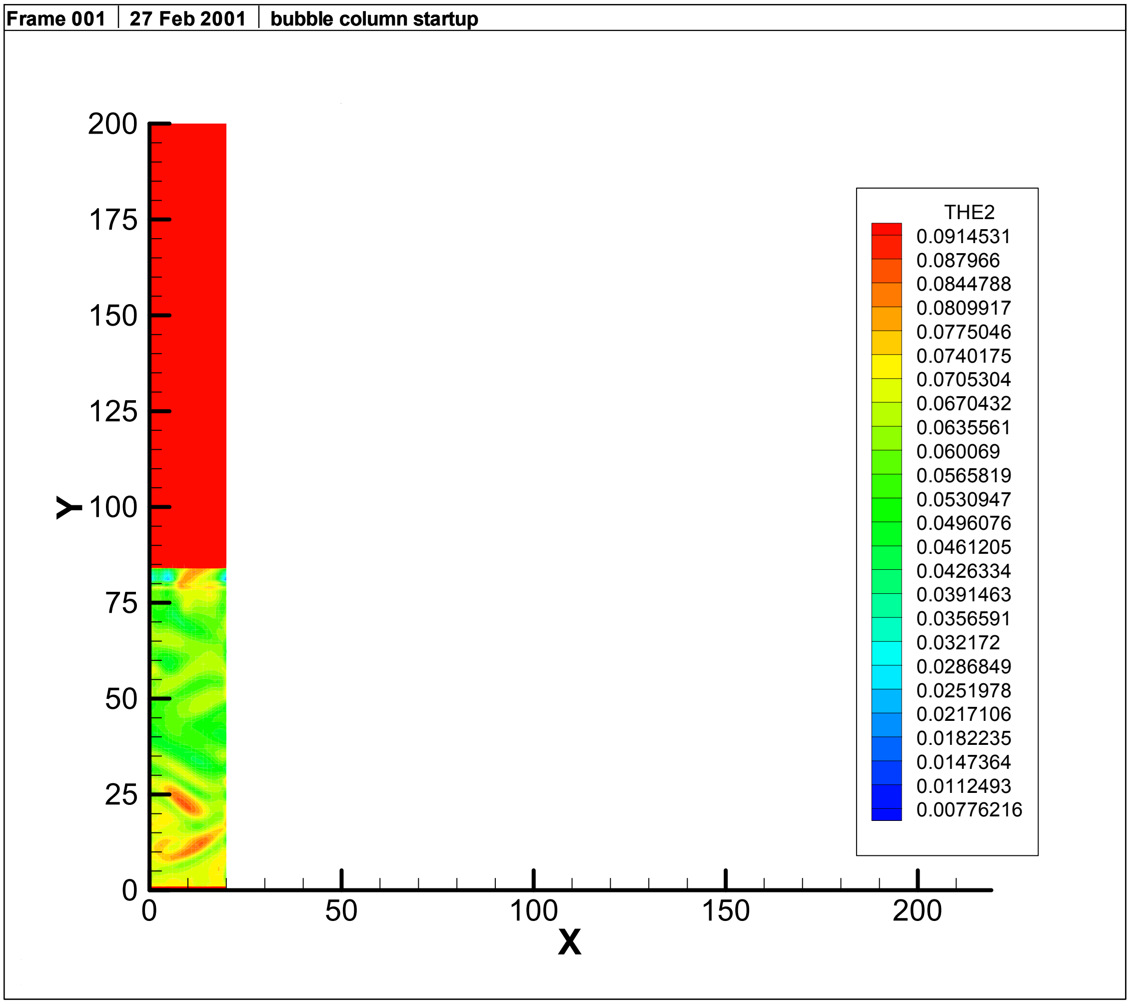

**Figure 6 Volume Fraction of Air for the 1-cm Grid Simulation**

With a 20-cm wide column and periodic boundary conditions, the velocity in the x-direction appears as stationary bands, as shown in Figure 7. Since this does not accurately represent the behavior of the bubble column, simulations were then performed using a width of 100 cm, with no changes to the height or depth.

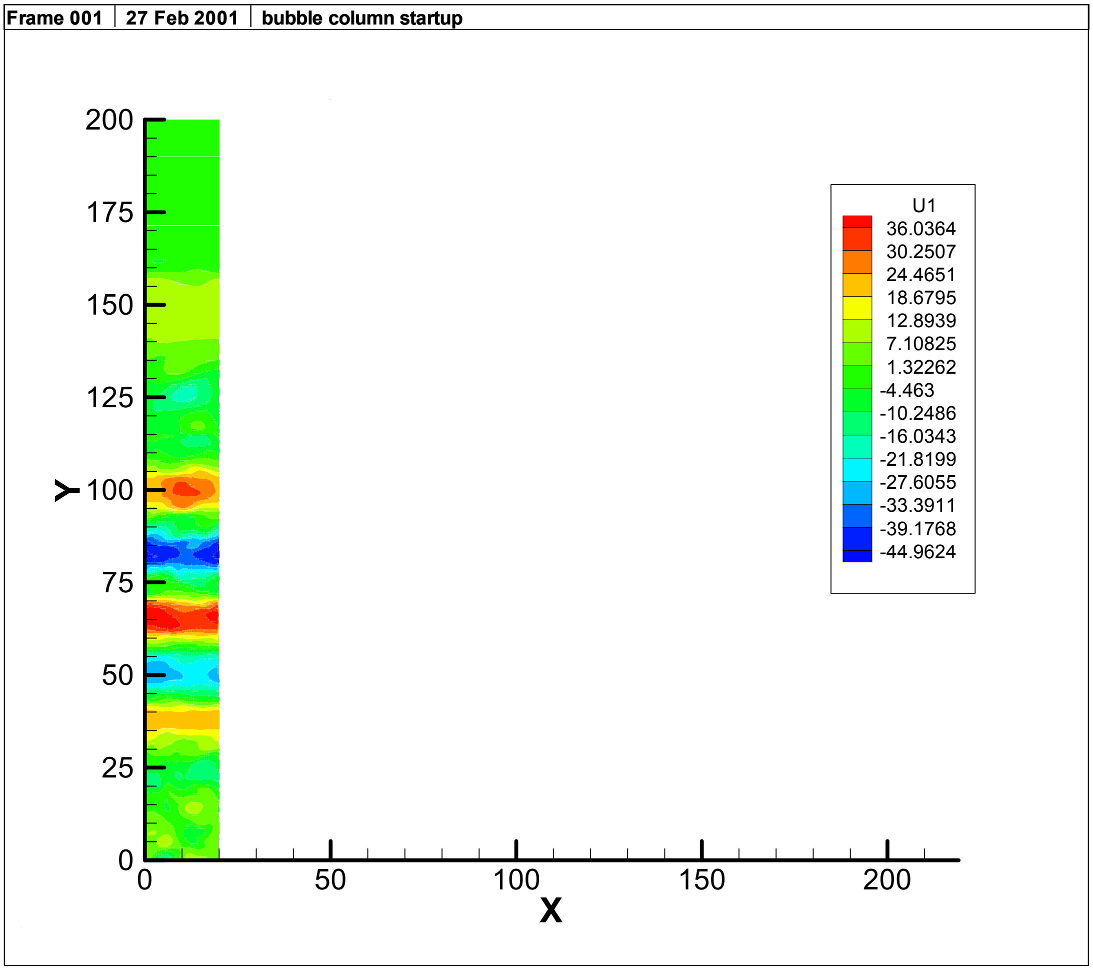

Figure 7 Contour Plot of Water Velocity in the X-Direction at t = 10 seconds

An obstacle involved in performing the 100-cm wide, 3D simulations is the length of time necessary for a sequential simulation. This could be improved by using a parallel CFDLIB code for simulations using periodic boundary conditions. Currently, there is no provision within the code for parallelization for use with periodic boundary conditions. Work began with consultants at the ISU high-performance computing facility to attempt to adapt the code for parallel use.

A possible work-around investigated this quarter was to utilize free-slip boundary conditions along the column walls. The parallel version of CFDLIB does work for this boundary condition. Simulations for both periodic boundary conditions and free-slip boundary conditions were performed using the conditions listed in Table 1. Comparisons were then made between the two types of boundary conditions. Examples of the results for this study are illustrated in Figures 8-11.

**Table 1 Simulation Conditions**

| | |
|---|---|
| Column height | 200 cm |
| Column width | 100 cm |
| Column depth | 2 cm |
| Bubble diameter | 1.5 mm |
| Inlet superficial air velocity | 2 cm/s |
| Initial water volume fraction, 0 cm to 40 cm height | 1.00 |
| Initial water volume fraction, 40 cm to 80 cm height | 0.75 |
| Initial water volume fraction, 80 cm to 120 cm height | 0.50 |
| Initial water volume fraction, 120 cm to 160 cm height | 0.25 |
| Initial water volume fraction, 160 cm to 200 cm height | 0.00 |

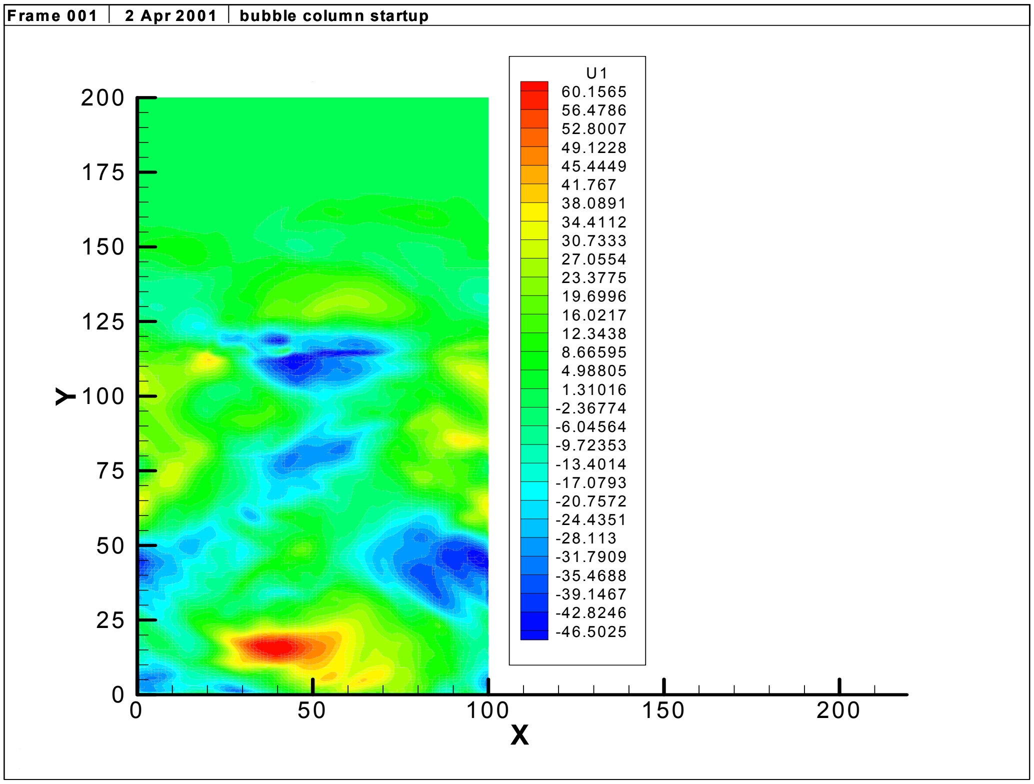

**Figure 8 Contour Plot of Water Velocity in the X-Direction at t = 10 seconds with Periodic Boundary Conditions**

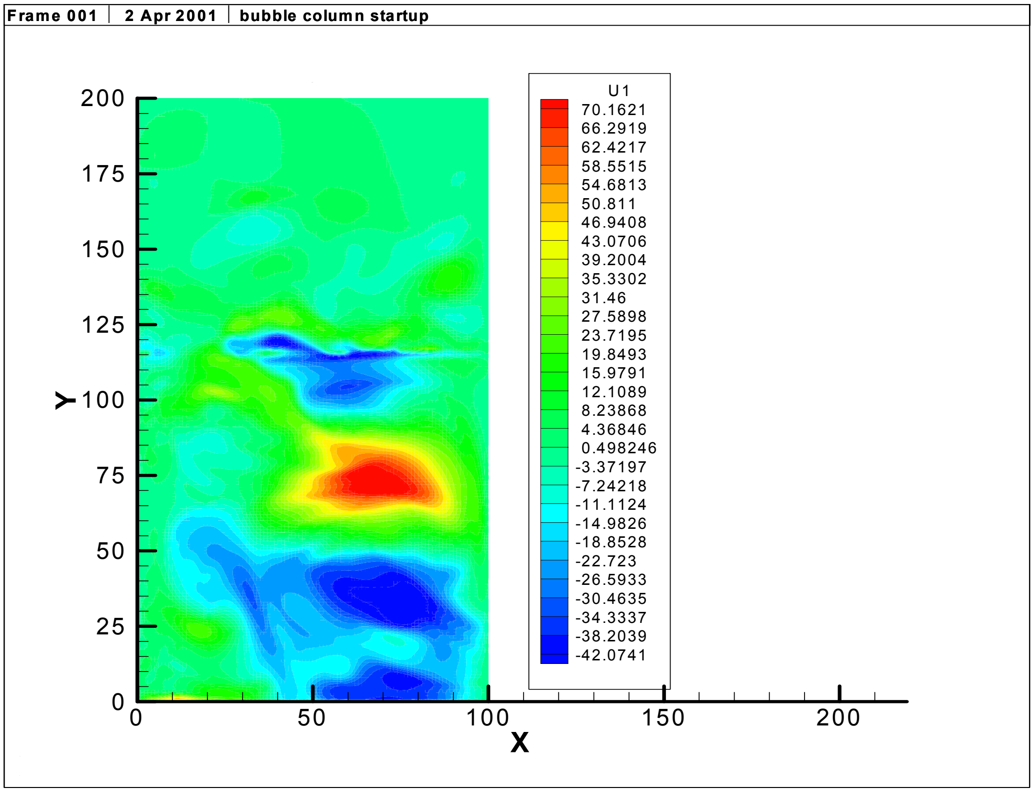

**Figure 9** Contour Plot of Water Velocity in the X-Direction at t = 10 seconds with Free-Slip Boundary Conditions

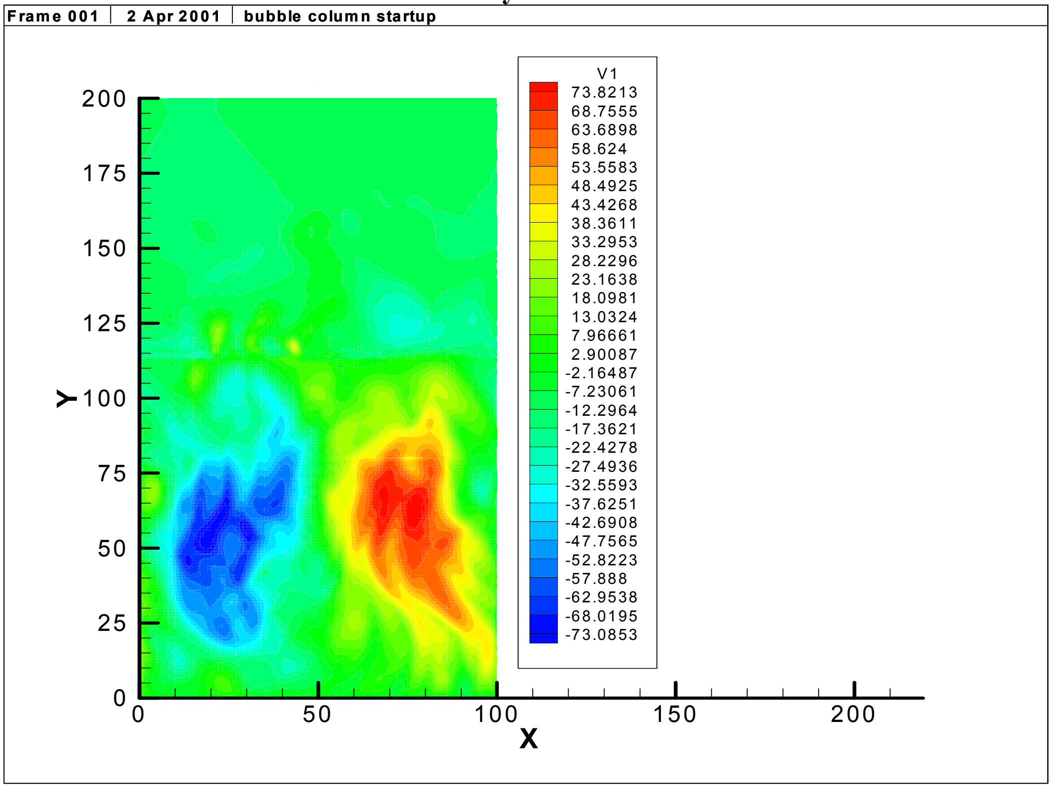

**Figure 10** Contour Plot of Water Velocity in the Y-Direction at t = 10 seconds with Periodic Boundary Conditions

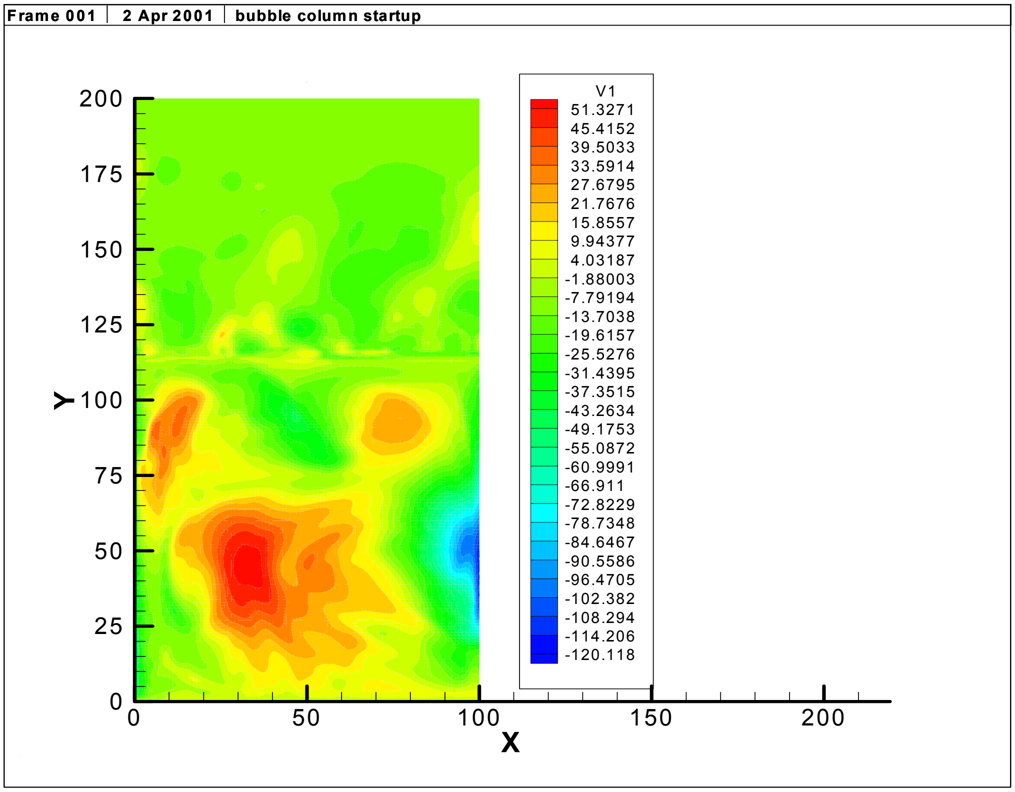

**Figure 11 Contour Plot of Water Velocity in the Y-Direction at t = 10 seconds with Free-Slip Boundary Conditions**

Figures 8 and 9 compare the differences in horizontal (x-direction) water velocity profiles for periodic and free-slip boundary conditions. For periodic boundary conditions, the highest magnitudes were observed at the walls at lower column heights, and as height increased, the higher velocities tended to occur in the center of the column. However, over time there should be no preferential location for high/low velocities. For free-slip boundary conditions, velocity magnitudes tended to be always highest in the center of the column.

Figures 10 and 11 compare the differences in vertical (y-direction) water velocity profiles for periodic and free-slip boundary conditions. The periodic boundary condition simulation resulted in high upward velocities along the right side of the column and high downward velocities on the left side of the column. Again, over time, there should be no preferential location. The free-slip boundary condition simulation resulted in high upward velocities always toward the center of the column. Velocity profiles in the z-direction were nearly the same for both types of boundary conditions, and had very low magnitudes.

The water volume fractions appeared to be more dispersed for the periodic boundary conditions, as shown in Figures 12 and 13. This is a strong indication that the characteristic length scales of the flow can be strongly influenced by the choice of the boundary conditions (in addition to the grid resolution).

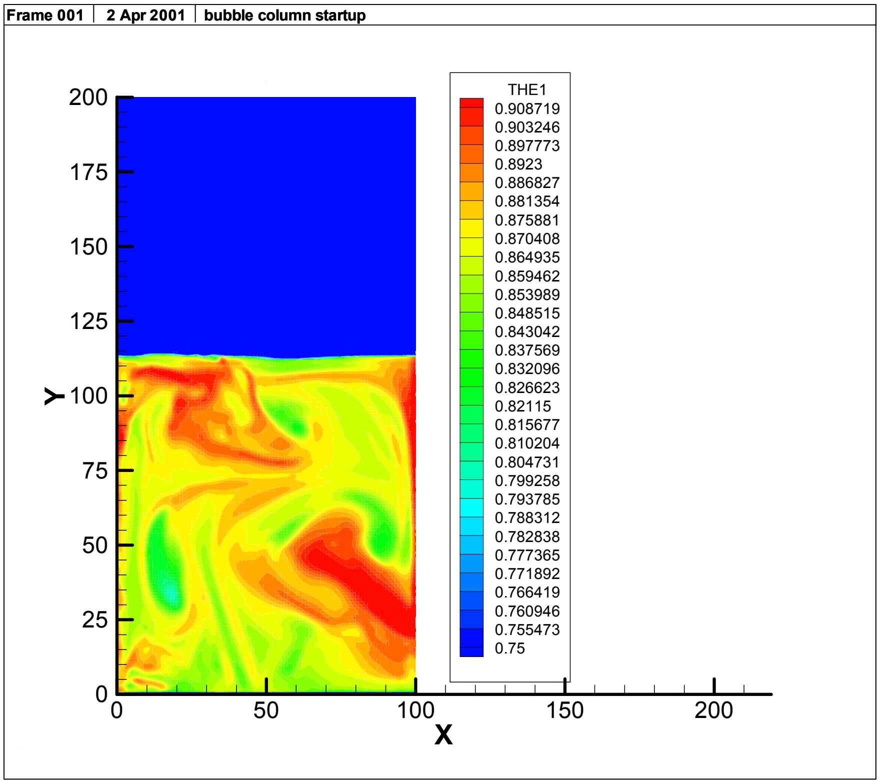

**Figure 12 Water Volume Fraction at 10 seconds with Free-Slip Boundary Conditions**

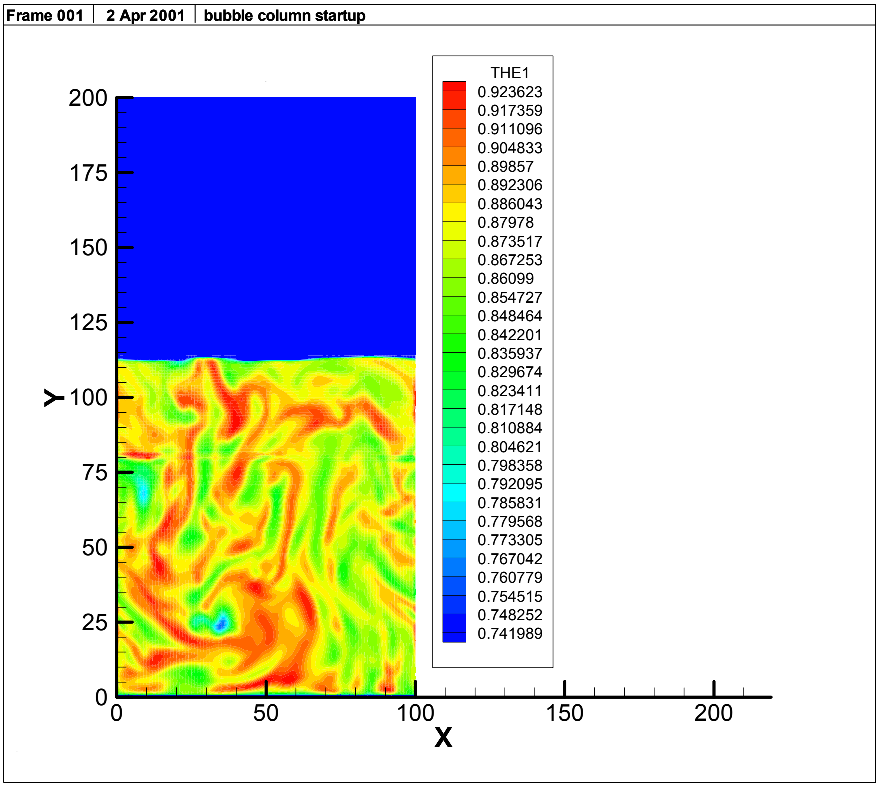

**Figure 13 Water Volume Fraction at 10 seconds with Periodic Boundary Conditions**

The effects of free-slip boundary conditions are best observed at locations a distance from the column walls. Simulations for this condition used a column depth of 2 cm, which may be too small a distance to properly utilize this type of boundary condition (at least with a 1-cm grid).

## Future Work

Plans for the next quarter include simulations for longer times (i.e., 20-30 seconds) to collect data for time-averaged quantities. Future simulations will also include setting an initial volume fraction of water equal to 1.0 up to a height of 150 cm, and an initial volume fraction of water equal to zero between 150 and 200 cm, to see if changes in the initial water volume fraction affect the flow patterns observed in simulations.

Due to the high cost of 3D simulations, we plan to test the validity of 2D simulations with periodic boundary conditions for representing the time-averaged statistics. This will be done by running a single "high-resolution" 3D simulation of sufficient length to collect statistics, and comparing these results to 2D simulations. In order to carry out these calculations, we plan to purchase an 8-processor SMP computer (Sun Fire 3800) during the next quarter. The availability of this machine should greatly increase the range of simulations that we will be able to run.