COMPUTATIONAL FLUID DYNAMICS SIMULATIONS OF OVERFLOW PATTERNS IN UTILITY-CHAMBER AND HYDRODYNAMIC STRESSES IN VEGETATION ZONE

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
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Keywords: (keyword-1, keyword-2, keyword-3, ...)

To my ____________,

____

ACKNOWLEDGMENTS

Firstly, I want to express my appreciation and respect to my

ABSTRACT

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NOMENCLATURE

BC	boundary condition
CFD	computational fluid dynamics
pHP	`phaseHydrostaticPressure`
pIOV	`pressureInletOutletVelocity`
tIKEI	`turbulentIntensityKineticEnergyInlet`
tMLDRI	`turbulentMixingLengthDissipationRateInlet`
α	fluid volume fraction
λ	stem occupancy fraction
ν	kinematic viscosity
ν_t	turbulent kinematic viscosity
ρ	density
τ	shear stress
θ	channel gradient
0	air phase
1	water phase
b	body
ic	inside the chamber
$\boldsymbol{cm}$	centimeter
$\boldsymbol{ft/s}$	foot per second
$\boldsymbol{ft}$	foot
$\boldsymbol{gal}$	gallon
$\boldsymbol{in}$	inch
$\boldsymbol{m/s}$	meter per second

$\boldsymbol{mgd}$ million gallons per day

$\boldsymbol{mm}$ millimeter

$\boldsymbol{m}$ meter

$\boldsymbol{s}$ second

$\boldsymbol{U}$ flow vector

D_{i} inlet diameter

D_{o} outlet diameter

D_{s} stem diameter

f_{b} body force term

h_{ss} sewage level in a steady state

n_{x}, n_{y}, n_{z} mesh division numbers in x, y, and z directions, respectively

Q_{in} inflow rate [mgd] or [tons/s]

t_{sm} time occuring the first submerging of outlet pipe

t_{ss} time to reach a steady state

V_{ic} initial volume in chamber

H chamber height

h stem height

L chamber length

p pressure

S inter-stem spacing

T stress tensor

W chamber width

U flow speed

CHAPTER 1
INTRODUCTION

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CHAPTER 2
SEWER CHAMBER DESIGN UNDER CRITICAL CONDITIONS USING COMPUTATIONAL FLUID DYNAMICS (CFD)

This chapter of the dissertation is a manuscript published in Desalination and Water Treatment, 108 (2018) 1-14, doi: 10.5004/dwt.2018.22019.

Transient sewage flow patterns inside a utility chamber are ...

Keywords: Computational fluid dynamics (CFD); OpenFOAM; Sewer design; manhole flow; urban runoff

2.1 Introduction

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2.2 Simulations

2.2.1 Governing equations

A brief summary of governing equations is as follows. As noted above, `interFoam` is a solver for two incompessible, isothermal, immiscible fluid, which uses the volume of fluid (VOD) phase fraction. The continuity and phase-fraction transport equations are

$$\nabla \cdot \boldsymbol{U} = 0 \tag{2.1}$$

and

$$\frac{\partial \alpha_1}{\partial t} + \nabla \cdot (\boldsymbol{U}\alpha_1) = 0 \tag{2.2}$$

respectively, and the momentum equation is

$$\frac{\partial (\rho \boldsymbol{U})}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) = -\nabla p + \nabla \cdot \boldsymbol{T} + \rho \boldsymbol{f}_b \tag{2.3}$$

where α_1 is the phase-fraction of water, ranging from 0.0 to 1.0. In Eq. (2.3), $\boldsymbol{T}$ in is the stress tensor and $\boldsymbol{f}_b$ is a body force term including gravity and surface tension, and the fluid density ρ and viscosity μ are estimated as

$$\rho = \alpha_1 \rho_1 + (1 - \alpha_1)\, \rho_0 \tag{2.4}$$

$$\mu = \alpha_1 \mu_1 + (1 - \alpha_1)\, \mu_0 \tag{2.5}$$

where the subscript 1 and 0 indicate water and air phases, respectively. More details of the solver can be found elsewhere [8, 9].

2.2.2 Manhole structure and meshing

Fig. 2.1 shows ...

.

.

This is summarized in Table 2.1.

Fig. 2.2 shows ..

2.3 Results and Discussions

2.3.1 Result section title

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2.3.2 Tantalizing phenomena

2.3.2.1 3D investigation

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2.3.2.2 2D investigation

2.3.3 Result verification and convergence test

In this section, we provide ...

2.4 Conclusion

In order to maintain ...

Acknowledgement This research used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant number ACI-1053575, and was financially supported by R. M. Towill Corporation, Honolulu, Hawaii, USA. The authors appreciate Mr. Jonathan Imai for his Solid Works drawing for the mesh generation.

	D	L	W	H
inlet pipe	16.0 in. (0.406 m)	16.0 ft (4.9 m)	–	–
outlet pipe	18.0 in. (0.457 m)	22.0 ft (6.7 m)	–	–
chamber	–	10.0 ft (3.0 m)	4.0 ft (1.2 m)	6.0 ft (1.8 m)

Table 2.1: Chamber and pipe dimensions. CFD simulations were conducted for three outlet diameters: 18, 20, and 24 inches (0.457, 0.508, and 0.610 meters, respectively).

	water	air	unit
fluid type	Newtonian	Newtonian	-
density, ρ	998.0	1.21	kg/m^3
kinematic viscosity, ν	1.0×10^{-6}	1.51×10^{-5}	m^2/s

Table 2.2: Properties of water and air used for `interFoam` simulations. In addition, the surface tension between water and air was set as 0.072 N/m and the gravitational acceleration (9.81m/s^2) was used.

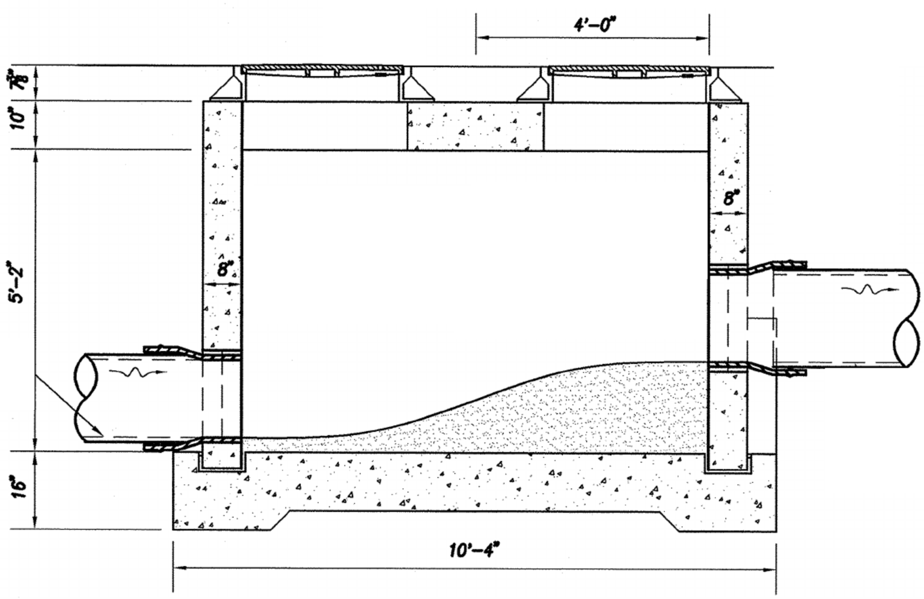
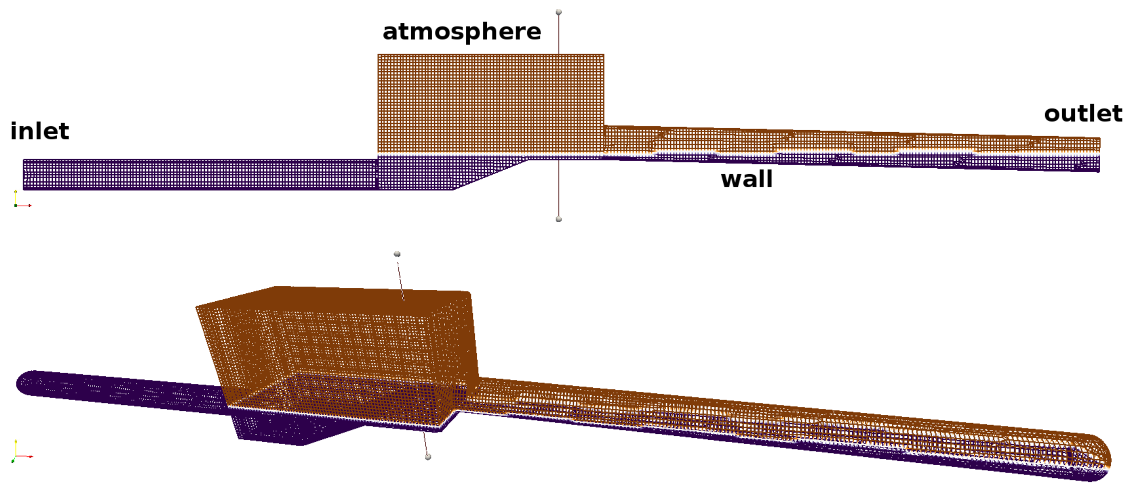


Figure 2.1: Section view of a real manhole.



(a)

(b)

Figure 2.2: Generated mesh structures: (a) 2D and (b) 3D views. The lower purple and upper brown regions represent water and air phases, respectively. The vertical line in the y-direction near the chamber outlet indicates a line through which sewage levels are calculated using OpenFOAM simulation results. In addition, x-direction is along the left inlet pipe, and z-direction is out of the $x-y$ plane.

CHAPTER 3
CALCULATION OF HYDRODYNAMIC STRESSES ON STEMS OF AN EMERGENT VEGETATION LAYER USING A UNIT-CELL MESHING METHOD: OPENFOAM SIMULATIONS

3.1 Introduction

Natural vegetation layers located in water bodies play an important role in ecosystems by providing shelter for aquatic life and reducing land erosion. For example, coastal vegetation layers such as coral reefs can be located in tropical oceans near the equator such as those we have surrounding the Hawaiian Islands, yet they have proven to be one on the most sensitively vulnerable groups threatened by global warming [10]. Although vital for biodiversity and shoreline protection, countless physical, chemical and biological stressors, as complexly coupled, make it difficult for researchers to predict consequential responses of vegetation due to future environmental changes [11, 12]. Sea level rise, for example, has increasingly been found to influence coastal degradation within the Hawaiian Islands, contributing to nearly 52–78% of the state's beaches experiencing increased rates of erosion [13]. Globally, since the mid-2010s, pilot programs with the intention of reducing vegetation loss, in developing rural places such as the Caribbean Islands, have been initiated for locally based communities to assess coastal vegetation reduction and implement restoration efforts [14]. However, efficient vegetation structures for the civil and environmental engineering practice to preserve the natural environment effectively, have not yet been established.

3.2 Simulation Setup

3.2.1 Mesh Generation

3.2.1.1 Meshing script

Fig. 3.1 shows ...

3.2.1.2 Vegetated (stem-occupied) cell

Fig. 3.2 shows the mesh grids of void spaces in the presence of a vertical, cylindrical stem embedded at the bed. The central hole indicates the internal volume of the stem. The unit-cell has seven boundaries, which include top, bottom, left, right, front, and back. The stem was assumed to have a rigid interior and smooth surfaces on which fluid velocity is assumed to be zero. A closer look of Fig. 3.2(a) indicates the mesh structure in the unit-cell has a symmetry about the two diagonal lines and x- and y-axes. In this case, a unidirectional flow far from the stem is calculated implicitly using a rectangle-like grid and a detouring flow around the stem is obtained using the polar grid.

3.2.2 Shear stress

Shear stress, in the engineering sector is one of the universally used properties to describe sediment and debris transport through an open channel[15]. The term "shear" is defined as the force acting tangential to another object's cross-sectional surface. A familiar analogy would be the river or stream bed flow above the bed surface. Domestic agencies such as the Vermont Agency of Natural Resources publish articles about construction projects near or around river banks affecting shear stress as they dictate the health of nearby ecosystems [16].

In her review paper published in 2012, Heidi Nepf presented an approach to predict bed stress for open-channel flow by defining it equal the the spatial average of the viscous stress at the bed. This relationship is also described as follows:

$$\tau_{bed} = \rho u_*^2 = \left\langle \mu \frac{\partial \bar{u}}{\partial z} \,|_{z=0} \right\rangle \tag{3.1}$$

For this approach, $\frac{\partial \bar{u}}{\partial z}$ is the velocity gradient normal to the surface above the vegetation bed surface [17].

3.3 Concluding Remarks

In this chapter, we ...

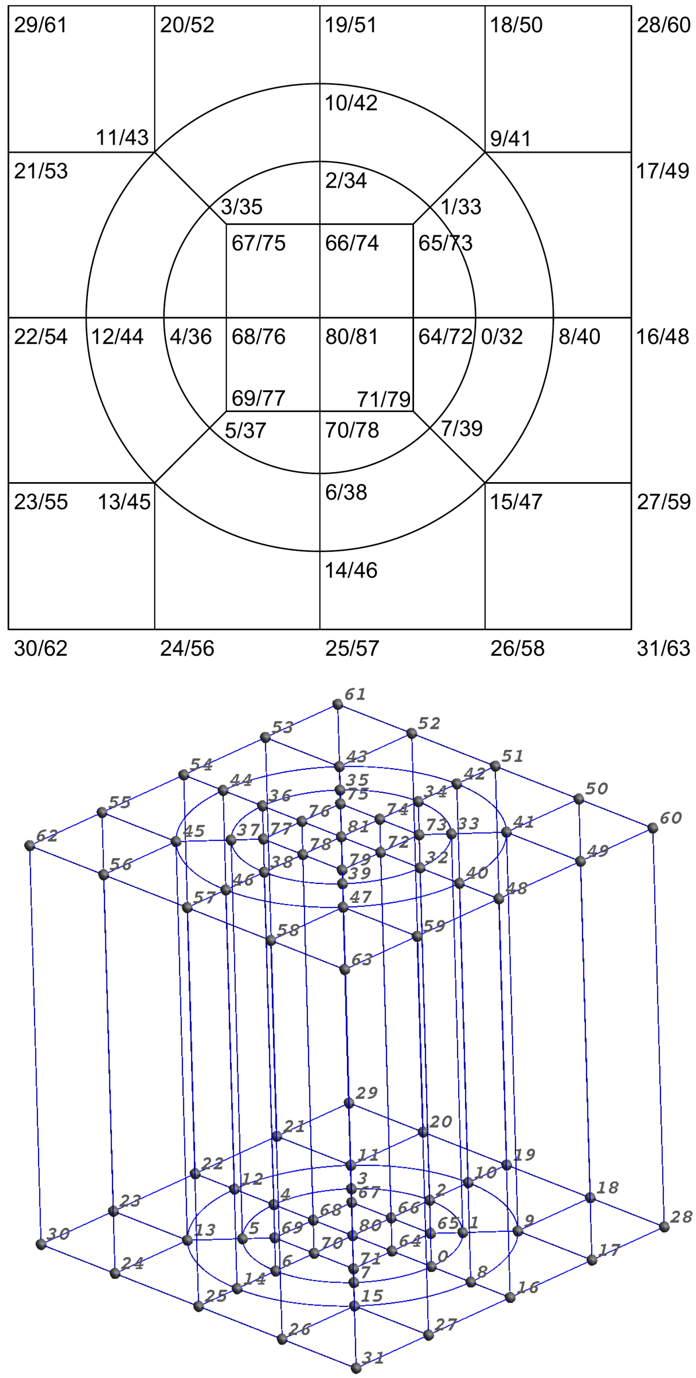
Given our research at this point, we indicate ....

Variables	Inlet	Outlet & Top	Side & Bottom Walls
$p - \rho g h$	Fixed-Flux-Pressure	Total-Pressure (0)	Fixed-Flux-Pressure
U	Variable-Height-Inlet	Pressure-Inlet-Outlet-Velocity	No-Slip (U=0)
α	Inlet-Outlet (1)	Inlet-Outlet (0)	Zero-Gradient ($\nabla\alpha = 0$)

Table 3.1: Boundary condition parameters for the coarse, moderate, and fine mesh.

Mesh Fineness	Number of Internal Points	Approximate Run Time
Coarse	29,484	0 hr 20 min
Moderate	69,888	1 hr 00 min
Fine	136,500	5 hr 30 min

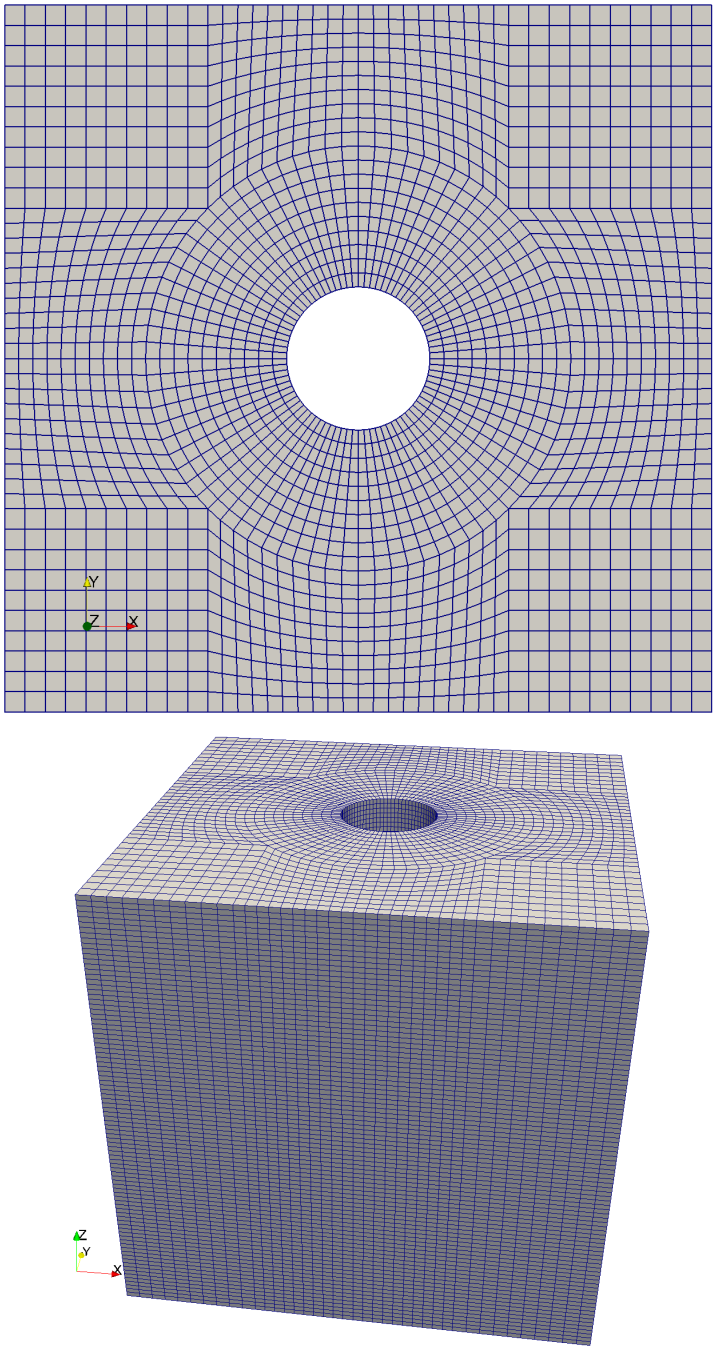
Table 3.2: Simulation run times for the coarse, moderate, and fine mesh.



(a)

(b)

Figure 3.1: Vertex indices shown in (a) 2D and (b) 3D view of a cylindrical stem in a rectangular box.



(a)

(b)

Figure 3.2: Mesh grid structure outside a rigid cylindrical stem, normally embedded on the bottom (bed) surface: (a) 2D top-view and (b) 3D side-view.

CHAPTER 4
CONCLUSION

Within the scope of the research for this thesis, computational fluid dynamics (CFD) simulations were conducted to assess the modeling capability to mimic, understand, and predict engineered phenomena in wastewater and stormwater applications.

The focus of Chapter 2, after introductory Chapter 1, was ....

The goal of Chapter 3 was ....

The results of the research completed ...

APPENDIX A
APPENDIX

A.1 Hollow and Filled Unit Stem Generation Using C++ and GNU Make Utility

Source code: `gen_blockMeshToFile-v8.tex`

```
#include <iostream>
#include <fstream>
#include <ctype.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
using namespace std;

int main (int argc, char **argv){
  char           cylinderType, comma ;
                 // hollow (h or H) or filled (f or F)
  double         Rinr = 0.5;
  double         HLCx = 2.0;
  double         HLCy = 2.0;
  int            nGrZ = 5;
  int            Ninr = 8;
  char           idSp,idX, idY;

  std::ifstream infile("blockMesh.param");
  cylinderType= 'F';
  infile    >> Rinr             // >> comma
            >> HLSq             // >> comma
            >> FLCz             // >> comma

  std::cout << "infile␣␣=␣" << "blockMesh.param" << endl;
  std::cout << "Rinr␣␣␣␣=␣" << Rinr << endl;
  std::cout << "HLSq␣␣␣␣=␣" << HLSq << endl;

```

```
 /* omitted */

  /* MERGEPATCHPAIRS */
  outfile <<"mergePatchPairs" <<endl;
  outfile <<"("<<endl;
  outfile <<");"<<endl<<endl;
  outfile <<  "//␣********************************␣//\n"<<endl;

  outfile.close();
  return 0;}
```

Makefile

```
# Makefile
version=v8
srcroot=gen_blockMeshToFile-$(version)
cxx=g++
# CXX = c++ compiler
# cxx=icpc
#
gbm:
        $(cxx) $(srcroot).cpp -o $(srcroot).x

hollow:
        cp -f blockMesh.param.default blockMesh.param
        sed -i 's/cylinderType/H/' blockMesh.param $(srcroot).x
        cp blockMeshDict_hollow \
                ./stem_hollow/stem_hollow/system/blockMeshDict
        cd ./stem_hollow/stem_hollow && blockMesh

filled:
        cp -f blockMesh.param.default blockMesh.param
        sed -i 's/cylinderType/F/' blockMesh.param $(srcroot).x
        cp blockMeshDict_filled \
                ./stem_filled/stem_filled/system/blockMeshDict
        cd ./stem_filled/stem_filled && blockMesh
```

A.2 MATLAB Script to calculate `alphaU`

The following script and associated text files were used to produce `AlphaU` datasets for each simulation time step. This MATLAB script was initially used until modifications were made directly in the OpenFOAM script to automatically calculate `alphaU`. As seen in the README.txt section, there are variables within the matlab script that will need to be changed depending on the OpenFOAM case and mesh size.

AlphaU.m

```
% Create Alpha-U Data Set
% Date Created: September 7, 2019
% Last Updated: September 12, 2019
% Created by: Tyler Tsuchida % Document Name: CreateAlphaU.m
% Location: /home/student/Documents/TylerTsuchida/TylerTsuchidaThesis/
% Description: This script is to create a new dataset, alphaU, for every timestep in an openFOAM simulation
%% Read alpha.water and U values from time-step file
%Some lines beyond this point may need revision
num_point_rows=136500; %number of data points within mesh -- given after U or alphawater header
num_boundary_rows=10500; %number of data points at boundaries -- given after boundary conditions are stated at end of U or alphawater
num_headerlines=22; %number of lines from line 1 of code to line before mes data is written
num_boundarylines=5340528; %number of lines from line 1 of code to line before boundary data is written
folder=3; %the next line of code lists all folders in your simulation directory, to skip invisible folders,
folder=1st time step folder on list
timestep=dir('/media/student/Elements/2019-10-25-Coarse/cavity_cFE_coarse0/cavity_cFE_coarse0'); %insert directory with all timesteps here
%Do not need to edit the code beyond this point
% ...
% ...
```

```
end
```

alphaU sections

alphaU_Header2.txt

```
object alphaU;
}
//************************************//
dimensions [0 1 -1 0 0 0 0];
internalField nonuniform List<vector>
5340000
(
```

alphaU_Footer1.txt

```
);
boundaryField
{
 DOWN_btm_F00 { type noSlip; }
 DOWN_btm_H10 { type noSlip; }
...
 DOWN_inn_F36 { type noSlip; }
 DOWN_inn_F46 { type noSlip; }
 merged_LEFT_inn_F40 { type flowRateInletVelocity; volumetricFlowRate
    constant 0.0075; extrapolateProfile false; value uniform (0.3197619
     -0 -0); }
 merged_RGHT_btm_F90 { type pressureInletOutletVelocity; value
    nonuniform List<vector> 10500 (
```

alphaU_Footer2.txt

```
); }
merged_FRNT_inn_F10 { type noSlip; }
merged_FRNT_btm_F00 { type noSlip; }
merged_BACK_inn_F16 { type noSlip; }
merged_BACK_btm_F06 { type noSlip; }
merged_ATOP_inn_F46 { type zeroGradient; }
merged_ATOP_btm_F96 { type zeroGradient; }
}
```

```

// *************************************//
```

README.txt

```
Sources for data files:
alphaU_generator.zip
alphaU_generator:
alphaU_Footer1.txt alphaU_Footer2.txt alphaU_Header2.txt calc_alphaU.m
    README.txt
All files listed above must be in the directory of all timestep folders
    for calc_alphaU.m to run properly.
Enter directory and other information in calc_alphaU.m as needed to
    match information of the desired run.
```

A.3 Symmetry Boundary Condition Shear Calculations

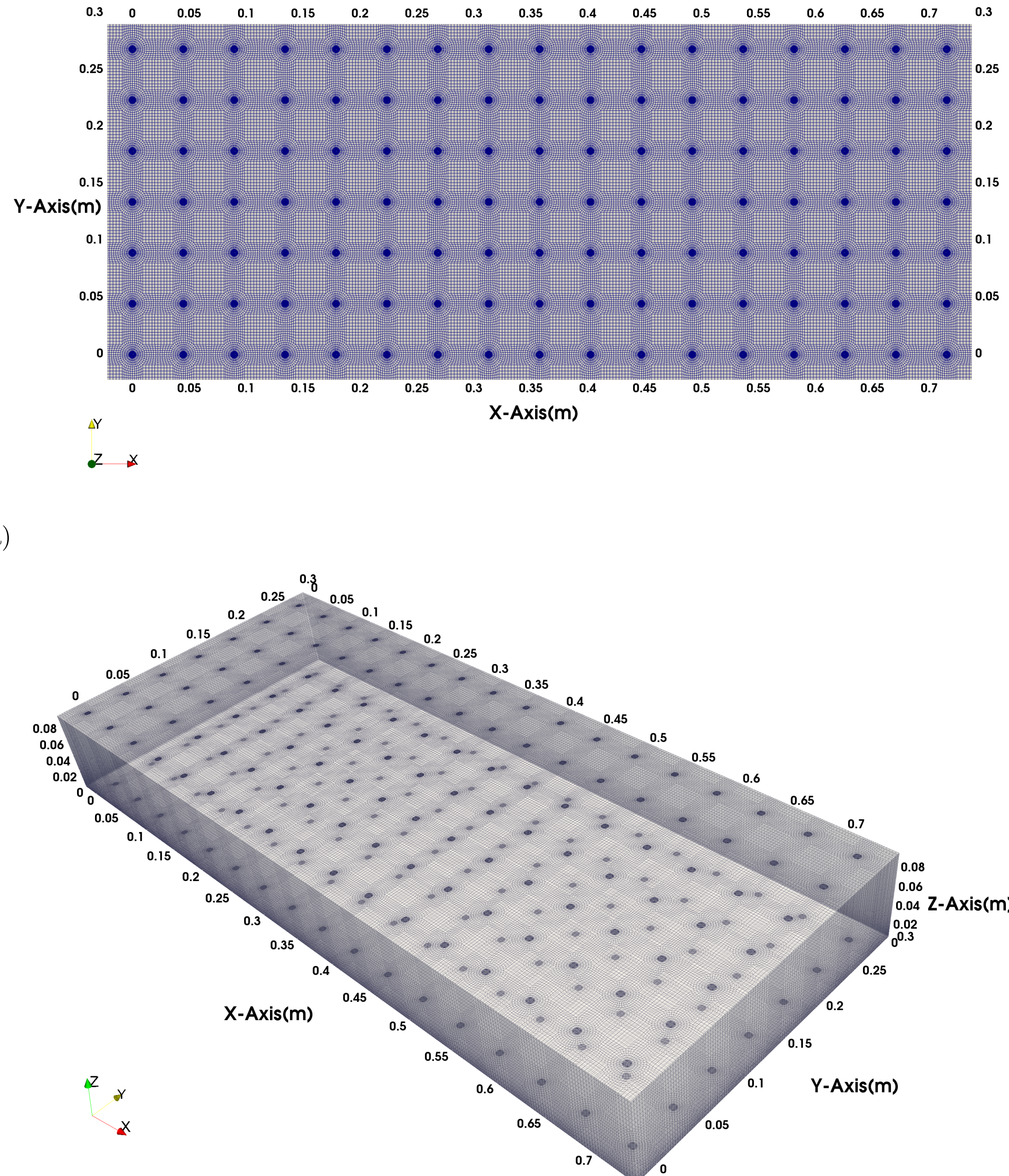
Along with the shear rate calculations presented in the paper, calculations were also performed on the fine, medium, and coarse meshes using `cyclic` boundary conditions. Also, shear rates of the checkerboard were also calculated as supplementary information.

Face Name	$\frac{\partial(\alpha U_x)}{\partial x}$	$\frac{\partial(\alpha U_x)}{\partial y}$	$\frac{\partial(\alpha U_x)}{\partial z}$	$\frac{\partial(\alpha U_y)}{\partial x}$	$\frac{\partial(\alpha U_y)}{\partial y}$	$\frac{\partial(\alpha U_y)}{\partial z}$
DOWN_Eab_merged	2.64E-02	6.91E-09	3.90E+00	–	–	–
HOLE_Eab	-1.49E-02	1.12E-07	-6.66E-11	–	–	–
HOLE_Eab	–	–	–	-1.01E-07	1.81E-02	8.54E-11
inlet	1.07E-03	0.00E+00	0.00E+00	–	–	–
outlet	1.07E-03	1.13E-09	-2.57E-04	–	–	–

Table A.1: Calculations of shear rate [1/s] using the fine mesh at time = 3.00s with front and back faces (`cyclic`).

A.4 Alternative Canopy Orientations

The following figures shows alternative configurations of 24 stems embedded on the bed surface.



(a)

(b)

Figure A.1: 0-0-0-0-0-0-0 stem orientation (a)2D and (3) 3D plot.

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