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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IN

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(DEGREE-AWARDEDMONTH) (DEGREE-AWARDED YEAR)

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(Committee Member No 3 FullName)

Keywords: (keyword-1, keyword-2, keyword-3, ...)

To my ____________,

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ACKNOWLEDGMENTS

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

ABSTRACT

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CHAPTER 1
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

1.1 Introduction

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1.2 Simulations

1.2.1 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

$$\nabla \cdot \boldsymbol{U} = 0 \tag{1.1}$$

and

$$\frac{\partial \alpha_1}{\partial t} + \nabla \cdot (\boldsymbol{U}\alpha_1) = 0 \tag{1.2}$$

respectively, and the momentum equation is

$$\frac{\partial (\rho \boldsymbol{U})}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) = -\nabla p + \nabla \cdot \boldsymbol{T} + \rho \boldsymbol{f}_b \tag{1.3}$$

where α_1 is the phase-fraction of water, ranging from 0.0 to 1.0. In Eq. (1.3), $\boldsymbol{T}$ 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

$$\rho = \alpha_1 \rho_1 + (1 - \alpha_1)\, \rho_0 \tag{1.4}$$

$$\mu = \alpha_1 \mu_1 + (1 - \alpha_1)\, \mu_0 \tag{1.5}$$

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

1.2.2 Manhole structure and meshing

Fig. 1.1 shows ...

.

.

This is summarized in Table 1.1.

Fig. 1.2 shows ..

1.3 Results and Discussions

1.3.1 Result section title

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1.3.2 Tantalizing phenomena

1.3.2.1 3D investigation

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1.3.2.2 2D investigation

1.3.3 Result verification and convergence test

In this section, we provide ...

1.4 Conclusion

In order to maintain ...

Acknowledgment 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 1.1: 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 1.2: 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 ($9.81 m/s^2$) was used.

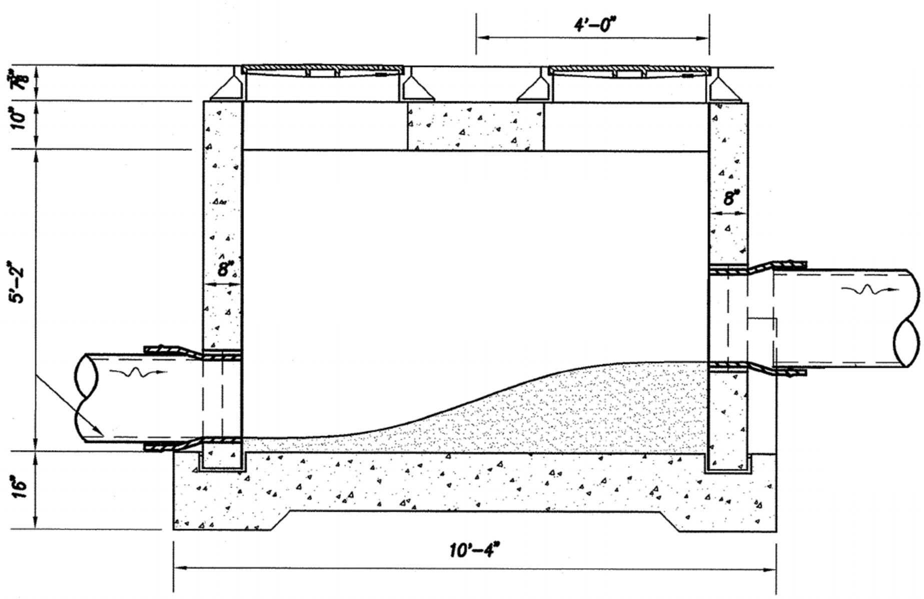


Figure 1.1: Section view of a real manhole.

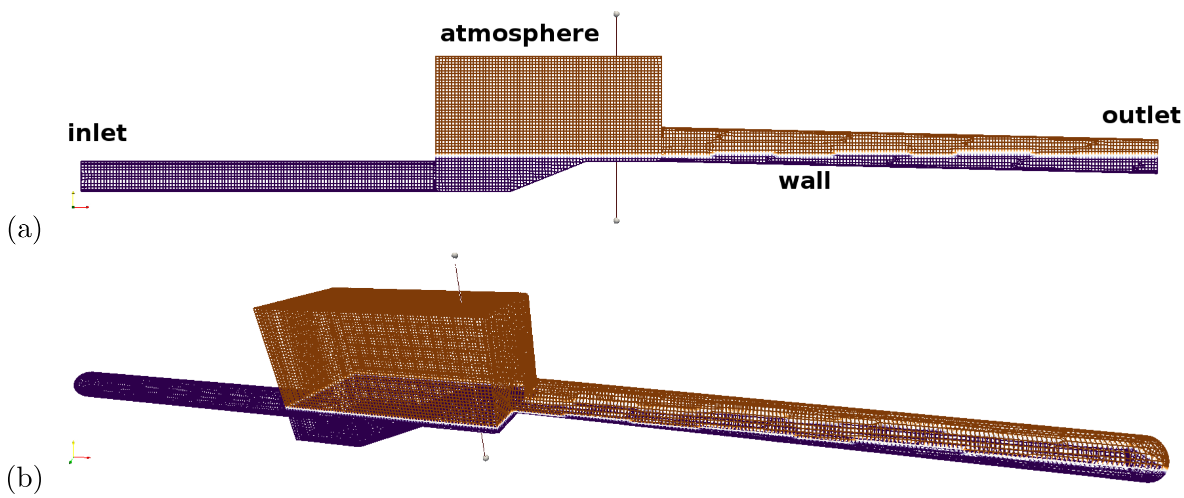


Figure 1.2: Generated mesh structures: (a) 2D and (b) 3D views. The lower purple and upper brown regions represent water and air phases, respectively. The vertical line in the y-direction near the chamber outlet indicates a line through which sewage levels are calculated using OpenFOAM simulation results. In addition, x-direction is along the left inlet pipe, and z-direction is out of the $x - y$ plane.

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

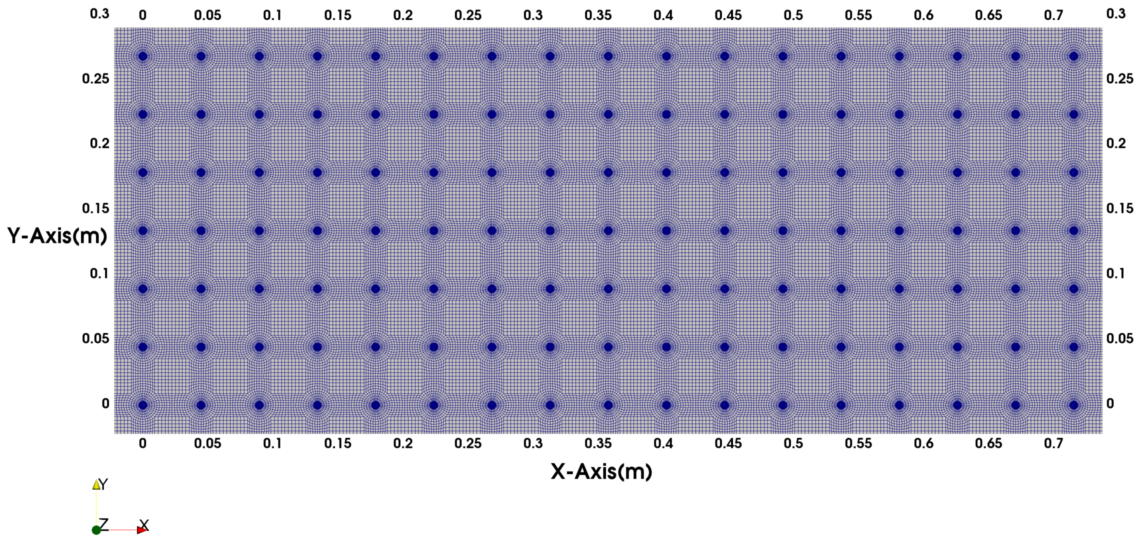
Along with the shear rate calculations presented in the paper, calculations were also performed on the fine, medium, and coarse meshes using `cyclic` boundary conditions. Also, shear rates of the checkerboard were also calculated as supplementary information.

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	–	–	–

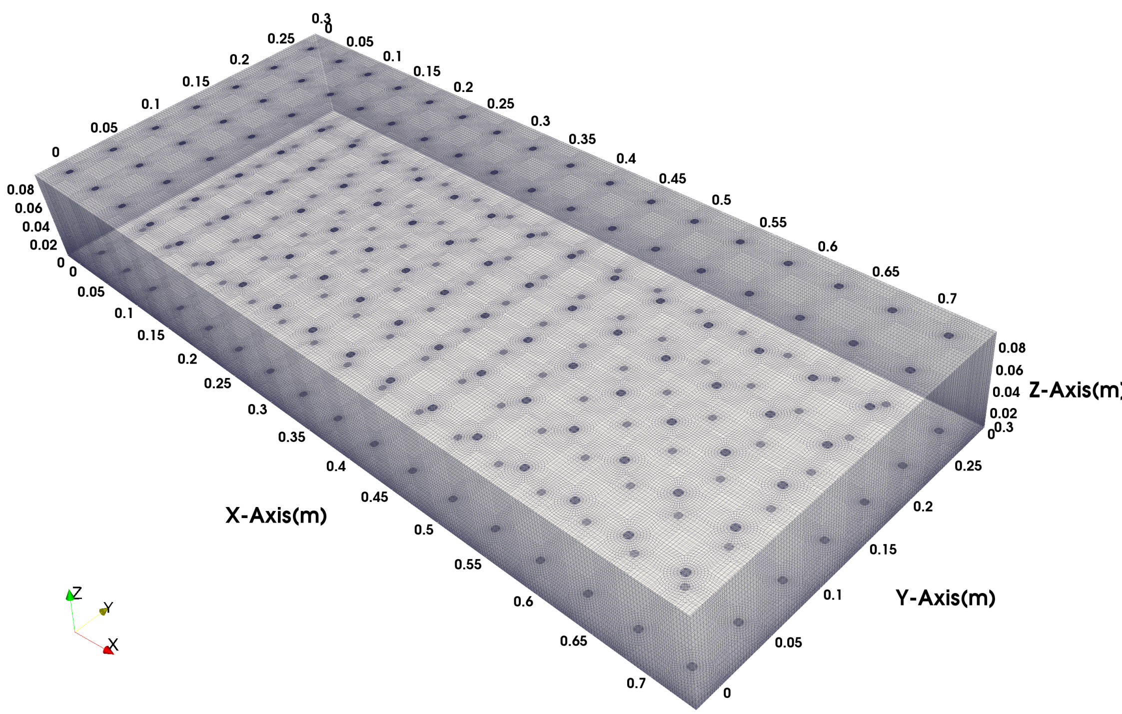
Table A.1: Calculations of shear rate [1/s] using the fine mesh at time = 3.00s with front and back faces (`cyclic`).

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.

BIBLIOGRAPHY

[1] M. Balogh, A. Parente, and C. Benocci. RANS simulation of ABL flow over complex terrains applying an enhanced $\kappa - \epsilon$ model and wall function formulation: Implementation and comparison for fluent and openfoam. *Journal of Wind Engineering and Industrial Aerodynamics*, 104:360 – 368, May 2012. 13th International Conference on Wind Engineering.

[2] F. Greifzu, C. Kratzsch, T. Forgber, F. Lindner, and R. Schwarze. Assessment of particle-tracking models for dispersed particle-laden flows implemented in openfoam and ansys fluent. *Engineering Applications of Computational Fluid Mechanics*, 10(1):30–43, May 2016.

[3] P. Kang, W. Lee, S. Lee, and A. Kim. Origin of structural parameter inconsistency in forward osmosis models: A pore-scale CFD study. *Desalination*, (accepted), 2017.

[4] A. Kim, S. Ki, and H. Kim. Research perspective of membrane distillation: multi-scale and multi-physics phenomena. *Desalination and Water Treatment*, 58:351–359, 2017.

[5] A. Kim, M. Park, and J. Mi. Computational fluid dynamics simulation of liquicel membrane using openfoam: implication for membrane distillation. *Desalination and Water Treatment*, 58:360–367, December 2017.

[6] J. Ahrens, B. Geveci, and C. Law. *ParaView: An End-User Tool for Large Data Visualization, Visualization Handbook*. Elsevier, 2005.

[7] U. Ayachit. *The ParaView Guide: A Parallel Visualization Application*. Kitware Inc., 2015.

[8] H. Weller, G. Tabor, H. Jasak, and C. Fureby. A tensorial approach to computational continuum mechanics using object-oriented techniques. *Computers in Physics*, 12(6):620–631, 1998.

[9] C. Greenshields. *OpenFOAM User Guide version 4.0*, June 2016.