

**Optimising Municipal Sewage Networks-Using  
Computational Fluid Dynamics**

**Case study: Tororo Municipality, Uganda**

**Esemu Joseph Noah**

**BSc.Ed (Hons) (BU)**

**BU/GS16/MIM/2**



**A dissertation submitted to the Department of  
Mathematics, Faculty of Science and Education in partial  
fulfilment of the requirements for the award of the Degree  
of Master of Science in Industrial Mathematics of**

**Busitema University**

**September, 2018**

**DECLARATION**

I **ESEMU JOSEPH NOAH**, hereby certify that this dissertation is a result of my original research work and to the best of my knowledge it has never been submitted for any degree award in any other university before and I present it without any reservations for external examination.

Name: **ESEMU JOSEPH NOAH**

Signature  Date 14/09/2018

<b>BUSITEMA UNIVERSITY LIBRARY</b>
CLASS No.: .....
ACCESS NO.: .....

## APPROVAL

This research work culminating into this dissertation was conducted under my guidance and supervision.

1. Professor Verdiana Grace Masanja

Qualifications: BSc (Maths and Physics), MSc. (Maths), MSc. (equalisation to German Masters of Physics), PhD (Fluid Mechanics)

Signature:




Date : 17th September 2018

2. Dr. Semwogerere Twaibu (PhD)

Qualifications: B.Sc (Educ, M. Sc. (Math), Ph.D) - Eng. Maths - Mech. Eng.

Signature:



Date:

19/09/2018

3. Dr. Awichi Richard (PhD)

Qualifications: BSc (Ed), MSc (Math) PhD (Maths Stat) JKU

Signature:



Date:

19/09/18

## **DEDICATION**

I would like to dedicate this work to the Almighty God for his grace, my Mother Akol Regina, Late Father Mzee Ebyeu Zerubbabel and all my brothers and sisters who have always strived to show me the true value of education. My dear wife, children and entire family, for all your support and inspiration.

## ACKNOWLEDGEMENTS

Success can never happen without the blessings of Almighty God as well as the support, encouragement and contributions from various individuals and organizations. First and foremost, I thank almighty God to the fullest for his blessings and having provided me with good health and for lighted me with the light of hope every time I found myself in difficult situations. My life here wouldn't have been comfortable without prayers and love from my family and friends.

I express my deep appreciation to Prof. Verdiana Grace Masanja, Dr. Nampala Hasifa and Mr. Joseph Ddumba Lwanyaga, my research supervisors, for their patient guidance, useful advice and warm encouragement for my research work. I would also like to thank Dr. Awichi Richard and Dr. Semwogerere Twaibu for their time devoted for reading my dissertation. I really appreciate my family for their support and encouragement to finish my study.

This research was funded by the RUFORUM Graduate Research Grant (GRG) through the Directorate of Graduate Studies, Research and Innovations, Busitema University. I gratefully acknowledge and appreciate the support.

My sincere thanks go to all staff members of Faculty of Science and Education, especially department of Mathematics. Special thanks go to Dr. Andama Edward, Dr. Olema David, Dr. Mike Seeti and all my lecturers for their continuous advice and words of encouragement. I also express my sincere appreciation to Eng. Patricia Nakanwagi of Makerere University for her support in learning the OpenFOAM tool. Your tips and guidance were vital to my work. Mr. Ocul Tomas Baker, Madam Abinyo Rachel and my Head teacher Mzee Iisat Ignatius for their moral support, encouragement and kind pieces of advice during my study.

Lastly, I express my gratitude to Madam Asekenye Sylvia, Mr. Okitoi Richard, staff of Masaba SS and all who have been directly or indirectly involved in this research project.

## TABLE OF CONTENTS

### PRELIMINARIES

DECLARATION.....	i
APPROVAL .....	ii
DEDICATION.....	iii
ACKNOWLEDGEMENTS .....	iv
TABLE OF CONTENTS .....	v
PRELIMINARIES.....	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
ACRONYMS AND ABBREVIATIONS.....	x
ABSTRACT.....	xii
CHAPTER ONE .....	1
INTRODUCTION.....	1
1.1 Background.....	1
1.2 Statement of the Problem .....	3
1.3 Justification of the Study.....	4
1.4 Objectives.....	4
1.4.1 Specific Objectives .....	4
1.5 Hypotheses.....	5
1.6 Significance of the Study .....	5
1.7 Theoretical and Conceptual Framework .....	5

1.8	Scope of the Study.....	6
<b>CHAPTER TWO .....</b>		<b>7</b>
<b>LITERATURE REVIEW .....</b>		<b>7</b>
2.1	Introduction.....	7
2.2	Sewage Transportation in Sewer Networks .....	7
2.3	Sewage Connections to the Sewer Networks.....	7
2.4	Modelling of Sewer Networks.....	8
2.4.1	Sewer Optimization Models.....	8
2.4.2	CFD Models .....	11
<b>CHAPTER THREE.....</b>		<b>13</b>
<b>MATERIALS AND METHODS .....</b>		<b>13</b>
3.1	Introduction.....	13
3.2	Study Site .....	13
3.3	Research Design.....	13
3.3.1	Design Constraints.....	14
3.4	Data collection.....	14
3.4.1	Field Conditions and Measurements Data.....	14
3.5	Model Presentation and Simulations.....	15
3.5.1	Sewer networks Design Optimization.....	15
3.5.2	CFD Modelling Method .....	17
<b>CHAPTER FOUR.....</b>		<b>30</b>
<b>MODEL ANALYSIS, RESULTS AND DISCUSSIONS.....</b>		<b>30</b>

4.1 Results of assessment and analysis .....	30
4.1.1 Sewer Network .....	30
4.1.2 Simulation Results .....	31
4.2 Discussions .....	41
4.2.1 Simulations of variable Velocity .....	41
4.2.2 Simulations of variable Pressure .....	42
4.2.3 Simulations of variable Pipe sizes .....	42
4.2.4 Simulations of effects of Acceleration due to Gravity .....	43
4.2.5 Running Simulations on refined mesh refinements.....	43
<b>CHAPTER FIVE .....</b>	<b>44</b>
<b>CONCLUSIONS AND RECOMMENDATIONS.....</b>	<b>44</b>
5.1 Conclusions.....	44
5.1.1 Conclusions for improvement of the sewer system infrastructure .....	44
5.1.2 Conclusions for improvement of the model simulations.....	45
5.2 Recommendations .....	46
5.2.1 Recommendations for improvement of the existing sewer network.....	46
5.2.2 Recommendations of work for future studies.....	47
<b>GLOSSARY OF TERMS.....</b>	<b>49</b>
<b>REFERENCES: .....</b>	<b>51</b>
<b>APPENDICES .....</b>	<b>53</b>
Appendix 1: Sites visited.....	53
Appendix 2: Pictures of visited sites .....	53



## LIST OF TABLES

Table 3.1: Coefficient values for $k - \varepsilon$ turbulence model .....	24
Table 3.2: Summary of the boundary conditions for simulations.....	25
Table 3.3: Shows the fluid properties for the sewer flow .....	28
Table 3.4: Presents the variables used in interFoam model solver .....	28
Table 4.1: The minimum slopes and pipe sizes for sewer pipes.....	31
Table 5.1: The minimum slopes and pipe sizes for sewer system .....	46

## LIST OF FIGURES

<b>Figure 3.1:</b> Showing computational geometry of the sewer.....	23
<b>Figure 3.2:</b> Shows a 2D Mesh generation for the sewer.....	26
<b>Figure 4.1:</b> Liquid and air flows inside a pipe for 0.5m diameter.....	32
<b>Figure 4.2:</b> The velocity field flow inside a pipe ( $\text{ms}^{-1}$ ).....	32
<b>Figure 4.3:</b> The pressure field flow inside a pipe ( $\text{m}^2\text{s}^{-2}$ ).....	32
<b>Figure 4.4:</b> Liquid and air flows inside a pipe for 1.0m diameter at 0 degrees.....	32
<b>Figure 4.5:</b> Liquid and air flows inside a pipe for 1.0m diameter at 3 degrees.....	32
<b>Figure 4.6:</b> The pressure field flow inside a pipe inclined at 3 degrees ( $\text{m}^2\text{s}^{-2}$ ).....	33
<b>Figure 4.7:</b> The pressure field flow inside a pipe ( $\text{m}^2\text{s}^{-2}$ ).....	33
<b>Figure 4.8:</b> The pressure field flow inside a pipe ( $\text{m}^2\text{s}^{-2}$ ).....	33
<b>Figure 4.9:</b> The velocity field flow inside a pipe ( $\text{ms}^{-1}$ ).....	34
<b>Figure 4.10:</b> A graph showing a plot of Pressure loss (Pa) against Length of a pipe (m).....	34
<b>Figure 4.11:</b> A graph showing a plot of Magnitude of velocity U ( $\text{ms}^{-1}$ ) against Length of a pipe x (m).....	35
<b>Figure 4.12:</b> A graph showing pressure (Pa) verse pipe length (m).....	36
<b>Figure 4.13:</b> A graph showing the magnitude of velocity ( $\text{ms}^{-1}$ ) against pipe length (m).....	36
<b>Figure 4.14:</b> A graph showing pressure loss (Pa) verses pipe length (m).....	37
<b>Figure 4.15:</b> The liquid and air flow in horizontal channel of 1.0m high.....	37
<b>Figure 4.16:</b> The velocity field flow in channel with initial internal field uniform (0 0 0) $\text{ms}^{-1}$ .....	37
<b>Figure 4.17:</b> The liquid and air flow in channel of 1.0m high inclined at 3 degrees.....	38
<b>Figure 4.18:</b> Liquid and air flows in channel 1.5m high inclined at 3 degrees.....	38
<b>Figure 4.19:</b> The velocity field flow in channel with initial internal field uniform (1 0 0) $\text{ms}^{-1}$ .....	38
<b>Figure 4.20:</b> A graph showing Velocity development of fluid in the Channel.....	38
<b>Figure 4.21:</b> A graph of Velocity filed against time in the Channel.....	39
<b>Figure 4.22:</b> A graph of velocity against time in the channel.....	39
<b>Figure 4.23:</b> Shows different simulations of Mesh generation.....	40
<b>Figure 4.24:</b> A graph showing pressure drop dependence on the mesh.....	40

## ACRONYMS AND ABBREVIATIONS

### ACRONYMS

1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
CFD	Computational Fluid Dynamics
CSF	Continuum Surface Force
CVs	Control Volumes
DIC	Diagonal-based Incomplete Cholesky
DILU	Diagonal-based Incomplete Lower-Upper
DNS	Direct Numerical Simulation
FVM	Finite Volume Method
INS	Incompressible Navier-Stokes Equation
FDM	Finite Difference Method
FEM	Finite Element Method
K-Epsilon	Kappa-Epsilon
NS	Navier-Stokes Equation
NWSC	National Water and Sewerage Corporation
OpenFOAM	Open source Field Operation And Manipulation
PbiCG	Preconditioned Bi-Conjugate Gradient

PDEs	Partial Differential Equations
PISO	Pressure Implicit with Splitting of Operators
PIMPLE	Combination of PISO and SIMPLE
PCG	Preconditioned Conjugate Gradient
RANS	Reynolds Average Navier-Stokes
RAS	Reynolds Average Simulation
RUFORUM	Regional Universities Forum for Capacity Building in Agriculture.
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
VOF	Volume of Fluid

## ABSTRACT

Two-phase pipe flow is a common occurrence in many industrial applications such as sewage, water, oil and gas transportation. Accurate prediction of liquid velocity, holdup and pressure drop is of vast importance to ensure effective design and operation of fluid transport systems. In this dissertation, simulations of a two-phase flow of air and sewage (water) are performed using open source software OpenFOAM. Numerical Simulations have been performed using varying dimensions of pipes as well as their inclinations. A Standard k- $\epsilon$  turbulence model and the Volume of Fluid (VOF) free water surface model is used to solve the turbulent mixture flow of air and sewage (water). Results show that the flow pattern behaviour is influenced by the pipe diameters as well as their inclination. A two dimensional, 0.5m diameter pipe of 20m length is used for the CFD approach based on the Navier-Stokes equations. It is concluded that the most effective way to optimize a sewer network system for Tororo Municipality conditions, is by adjusting sewer diameters and slope gradients and expanding the number of sewer network connections of household and industries from 535 (i.e. 31.2% of total) to at least 1,200 (70% of total).

### **Keywords:**

Computational Fluid Dynamics (CFD); OpenFOAM; Optimal Design problem; Municipal Sewer network, Simulation, diameter, flow rate and pressure drop.

## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background

In urban development history, Municipal Sewage systems were built to rapidly collect rain runoff, wastewater and sewage. These networks consist of pipes, pumping stations, force mains, manholes, and other facilities required to collect and transport wastewater (Moeini & Afshar, 2017). Research on urban drainage pipelines focuses on hydraulics such as pipe slopes and flow rate so that sewage and faecal sludge are to be delivered efficiently (Han, 2012). The flows at or in the proximity of these structures are typically highly turbulent and often characterized with changes between open channel (free surface) and pressurized conditions. Such turbulent flows frequently involve complex interactions between air and water (Lopes, P., 2013) as in the case of manholes with multiple in/out pipes, stepped spillways, and flow network structures. The latter structures are typically composed by an entrance manhole and inflow, overflow, and underflow conduits. The main design challenge of the network structure is the allowance of overflows only after underdrain capacity is exceeded, while minimizing head losses that reduce the underdrain flow capacity. A second challenge is the prevention of significant backwater effects.

In hydraulic structures such as sewers and spillways, the air in the flow is important, perhaps an indispensable design factor (Leandro & Carvalho, 2013). The presence of air in wastewater (1) increases the bulk of the flow thus influencing the height of the chute side walls, (2) prevents the damage of the chute caused by cavitation, (3) increases the momentum when the air within the boundary layer reduces the shear stress and (4) re-oxygenates the water flow which contributes to the downstream river quality and the preservation of aerobic species (Leandro & Carvalho, 2013).

## REFERENCES:

- Afshar, M. H., Shahidi, M., Rohani, M., & Sargolzaei, M. (2011). Application of cellular automata to sewer network optimization problems. *Scientia Iranica*, 18(3 A), 304–312. <https://doi.org/10.1016/j.scient.2011.05.037>
- Afshar, M. H., Zaheri, M. M., & Kim, J. H. (2016). Improving the efficiency of Cellular Automata for sewer network design optimization. *Procedia Engineering*, 154, 1439–1447. <https://doi.org/10.1016/j.proeng.2016.07.517>
- Alizadehdakhel, A., Rahimi, M., Sanjari, J., & Abdulaziz, A. (2009). CFD and artificial neural network modeling of two-phase flow pressure drop ☆, 36, 850–856. <https://doi.org/10.1016/j.icheatmasstransfer.2009.05.005>
- Alizadehdakhel, A., Rahimi, M., Sanjari, J., & Alsairafi, A. A. (2009). CFD and artificial neural network modeling of two-phase flow pressure drop. *International Communications in Heat and Mass Transfer*, 36(8), 850–856. <https://doi.org/10.1016/j.icheatmasstransfer.2009.05.005>
- Ambrosio, C. D., Lodi, A., Wiese, S., & Bragalli, C. (2014). Mathematical Programming techniques in Water Network Optimization, (March).
- Aziz, M. A., Imteaz, M. A., Huda, N., & Naser, J. (2014). Optimise inlet condition and design parameters of a new sewer overflow screening device using numerical model. *Water Science and Technology*, 70(11), 1880–1887. <https://doi.org/10.2166/wst.2014.422>
- Chen, Z., Han, S., Zhou, F. Y., & Wang, K. (2013). A CFD Modeling Approach for Municipal Sewer System Design Optimization to Minimize Emissions into Receiving Water Body. *Water Resources Management*, 27(7), 2053–2069. <https://doi.org/10.1007/s11269-013-0272-9>
- Dufresne, M., Vazquez, J., Terfous, A., Ghenaim, A., & Poulet, J. B. (2009). Experimental investigation and CFD modelling of flow, sedimentation, and solids separation in a combined sewer detention tank. *Computers and Fluids*, 38(5), 1042–1049. <https://doi.org/10.1016/j.compfluid.2008.01.011>
- Duque, N., Duque, D., & Saldarriaga, J. (2017). Dynamic Programming over a Graph Modeling Framework for the Optimal Design of Pipe Series in Sewer Systems. *Procedia Engineering*, 186, 61–68. <https://doi.org/10.1016/j.proeng.2017.03.208>
- Fund, A. D. (2008). UGANDA : KAMPALA SANITATION PROGRAMME ENVIRONMENTAL AND SOCIAL IMPACT ASSESSMENT SUMMARY (ESIA ). *Water and Sanitation*, (July,2008).
- Greenshields, C. J. (2015). OpenFOAM, (December).
- Greenshields, C. J. (2017). OpenFOAM, (July).
- Guo, Y., Walters, G., Khu, S., & Keedwell, E. (2006). Optimal Design of Sewer Networks using hybrid cellular automata and genetic algorithm. *Computing in Civil Engineering*.
- Haghighi, A., & Bakhshipour, A. E. (2012). Optimization of Sewer Networks Using an Adaptive Genetic Algorithm. *Water Resources Management*, 26(12), 3441–3456. <https://doi.org/10.1007/s11269-012-0084-3>

- Han, P. D. (2012). *Concise Environmental Engineering*.
- Khatir, Z., Thompson, H., Kapur, N., Toropov, V., & Paton, J. (2012). Multi-objective Computational Fluid Dynamics (CFD) design optimisation in commercial bread-baking. *Applied Thermal Engineering*. <https://doi.org/10.1016/j.applthermaleng.2012.08.011>
- Leandro, J., & Carvalho, R. F. De. (2013). Free-surface flow interface and air-entrainment modelling using OpenFOAM Supervisors.
- Marley, C., & Systems, P. (2009). uPVC Sewer & Drainage Systems.
- Mazumder, Q. H. (2012). CFD analysis of the effect of elbow radius on pressure drop in multiphase flow. *Modelling and Simulation in Engineering, 2012*. <https://doi.org/10.1155/2012/125405>
- Ministry of Water. (2014). Water and Environment Sector Performance Report 2014. *Water Development*, (October).
- Moeini, R., & Afshar, M. H. (2017). Arc Based Ant Colony Optimization Algorithm for optimal design of gravitational sewer networks. *Ain Shams Engineering Journal, 8*(2), 207–223. <https://doi.org/10.1016/j.asej.2016.03.003>
- Mugisha, S. (2004). Short-Term Initiatives to Improve Water Utility Performance in Uganda: The Case of the National Water and Sewerage Corporation, *97*(September 2002), 1–8.
- National Water and Sewerage Corporation. (2010). *Annual Report*.
- Park, S. M. (2014). Numerical Simulation of Core- Annular Flow in a Curved Pipe, *2625*(2625), 70.
- Petit-Boix, A., Roigé, N., de la Fuente, A., Pujadas, P., Gabarrell, X., Rieradevall, J., & Josa, A. (2016). Integrated Structural Analysis and Life Cycle Assessment of Equivalent Trench-Pipe Systems for Sewerage. *Water Resources Management, 30*(3), 1117–1130. <https://doi.org/10.1007/s11269-015-1214-5>
- Rohani, M., & Afshar, M. (2016). Optimal design of Sewer network using Cellular Automata, *1*(October), 1–17. Retrieved from <http://article.scirea.org/pdf/57001.pdf>
- Rohani, M. and A. M. H. (2015). GA – GHCA model for the optimal design of pumped sewer networks, (February). <https://doi.org/10.1139/cjce-2014-0187>
- SappcoSa Damman, F. (2009). Upvc pipes and fittings. *Publication P.3, 01*(5), 1–38.
- UBOS. (2016). National Population and Housing Census 2014, Uganda. Main Report. *Uganda Bureau of Statistics*, (March), 1–108.
- Versteeg, H., K., and Malalasekera, W. (2005). *An Introduction to computational fluid dynamics. The finite volume method*. Longman Group Ltd.
- Water, B. Y. N., & Corporation, S. (2015). Management of sewage in urban areas, (March).