UNIVERSITÀ DEGLI STUDI DI SALERNO

Department of Industrial Engineering

Master's Degree in Chemical Engineering

Analysis of condensation phenomena in fiber-based cup

Thesis in

Transport Phenomena

Supervisors:

Prof. Eng. Gaetano Lamberti

Prof. Eng. Diego Caccavo

Prof. Eng. Anette Larsson

Dr. Eng. Raffaella De Piano

Candidate:

Antonia Calabrese

Number:0622201525

Academic Year 2023/2024

CHALMERS
UNIVERSITY OF TECHNOLOGY

Part of this work was developed during the Erasmus project at Chalmers University of Technology, Göteborg, Sweden. It was performed at the Department of Chemistry and Chemical Engineering, in the Division of Applied Chemistry, under the supervision of Prof. Anette Larsson.

Alle mie Persone.

Alla Donna che mi ha insegnato tanto.

E a Me stessa.

This text was printed in-house, in Times New Roman

The scheduled date for the thesis discussion is 20/12/2024 Fisciano, (date of printing)

Tables of contents

Tables of contents I

Table of figures IV

Table of tables VII

Abstract IX

Introduction 1

1.1 Single-use packaging ____ 2

1.1.1 Environmental impact 3

1.2 Paper and paperboard packaging ____ 7

1.2.1 How to make paperboard 7

1.2.2 Fiber-based cup 12

1.3 Hygroscopic materials ____ 16

1.3.1 Condensation phenomena 16

1.4 Aims ____ 20

Materials and methods 21

2.1 Materials ____ 22

2.1.1 Fiber-based cups 22

2.2 Methods ____ 24

2.2.1 Bulk density 24

2.2.2 Water content 27

Modeling 31

3.1 Physics of the system ____ 32

3.1.1 Sorption equation 32

3.1.2 Adsorption isotherm 33

3.1.3 Transport Equations 35

3.2 Model implementation ____ 40

3.2.1 Assumptions 40

3.2.2 Geometry 40

3.2.3 Parameters 41

3.2.4 Boundary conditions 42

3.2.5 Implementation in the Software 45

Results and discussion 47

4.1 Experiment results ____ 48

4.1.1 Bulk density 48

4.1.2 Experimental water content 49

4.1.3 Modified isotherm 53

4.2 Modeling results ____ 54

4.2.1 Moisture content comparison with experiments 54

4.2.2 Temperature and Water Concentration profiles 55

4.2.3 Relative humidity and Liquid saturation profiles 57

4.2.4 Moisture diffusivity equals zero 61

4.3 Parametric sweep ____ 63

4.3.1 Different thickness 63

4.3.2 Different external conditions 65

Conclusions 69

References 73

Table of figures

Figure 1. Primary, secondary, and tertiary packaging.[1] 2
Figure 2. Single-use plastic waste.[5] 4
Figure 3. Plastic Packaging Banned and Fiber-Based Packaging Approved. 5
Figure 4. Mechanical process for pulp.[8] 7
Figure 5. The chemical process for pulp.[8] 8
Figure 6. Process for recycling fiber.[8] 9
Figure 7. Simplified diagram of the forming process.[8] 10
Figure 8. Principal features in the manufacture of paper/paperboard – the number of headboxes will vary on the product.[8] 11
Figure 9. Different sizes of paper cups. 13
Figure 10. Design elements of a single-wall paper cup adapted from Mohan and Koukoulas (2004)[7] 14
Figure 11. Single-wall paper cup manufactured by SOLO.[7] 14
Figure 12. Double-wall paper cup manufacturing by Seda Packaging showing the outer wall.[7] 15
Figure 13. Double-wall paper cup with Thermolite™ insulation from LBP Manufacturing.[7] 15
Figure 14. Heterogeneous condensation.[12] 17
Figure 15. Film condensation on a vertical wall.[13] 18
Figure 16. Temperature gradient. 19
Figure 17. Concentration gradient. 19
Figure 18 Small (a) and big (b) cups. 22
Figure 19. Delamination material. 24
Figure 20. Thermobalance XM 60 26
Figure 21. Known volumes 26
Figure 22. Cups sequence for the different times. 27
Figure 23. Section of the measurement (a) and know volume (b). 28
Figure 24. Thermobalance with samples inside. 29

Figure 25. Example of fiber-based porosity.[14]...32

Figure 26. Adsorption isotherm from values of literature. 33

Figure 27. Isotherm implemented in COMSOL. 35

Figure 28. Geometry COMSOL Multiphysics software 1D. 40

Figure 29. 1D representation of the system geometry; the symmetry axis x=0..42

Figure 30. Physics chosen in COMSOL Multiphysics. 45

Figure 31. Implementation of adsorption isotherm. 45

Figure 32. Heat transfer in COMSOL Multiphysics software. 46

Figure 33. Step function for the cold temperature. 46

Figure 34. Mass transfer in COMSOL Multiphysics software. 46

Figure 35. Experimental data for small and big cups. 49

Figure 36. Images of the cups at different times: 30 minutes (a), 1 hour (b), 2 hours (c) and 6 hours (d). 51

Figure 37. Modified isotherm..53

Figure 38. Comparison between experimental data and modeling data. 55

Figure 39. Temperature (a) and Concentration (b) profiles. 56

Figure 40. Relative humidity (a) and Liquid saturation (b) profiles. 58

Figure 41 Comparison of water content with diffusivity of 1.1×10^{-12}[m^2/s] and 0[m^2/s], at 22°C and 37% relative humidity. 61

Figure 42. Water content (a) and liquid saturation (b) at different thickness, at 22.4°C and 37%...64

Figure 43. Parametric sweep at different external conditions.............................66

Table of tables

Table 1. Difference key between plastic and paper for the impact. 5
Table 2. General parameters for a small cup(a). 23
Table 3. General parameters for big cup(b). 23
Table 4. Dimensions of Big cups to calculate the volume. 25
Table 5. Dimensions of Small cups to calculate the volume. 25
Table 6. Calculating volume...25
Table 7. External room conditions were taken with the probe. 27
Table 8. Chosen times. 28
Table 9. Constant parameter in COMSOL Multiphysics software. 41
Table 10. Values calculated for the bulk density (small). 48
Table 11. Values calculated for the bulk density (big). 48
Table 12. Values from "Modified isotherm" 57
Table 13. Values for the partial pressure of the water vapor and the saturation pressure at 0°C. 59
Table 14. Calculation of Liquid saturation with equation (4.2). 60
Table 15. Different conditions for the parametric sweep. 65
Table 16 . Values for the partial pressure of the water vapor and the saturation pressure at 0°C. 66
Table 17. External conditions and the corresponding dew point. 67

Abstract

The growing reduction in the production and use of plastics has brought about new challenges in the packaging industry, pushing research toward more innovative and sustainable solutions. Among these alternatives, paper cups have emerged as a promising choice. However, they present unique challenges, primarily due to their hygroscopic properties. These materials tend to absorb moisture from the surrounding environment, which can lead to a decrease in their structural integrity when used to contain cold liquids. In such scenarios, condensation forms on the outer surface of the cup, and unlike plastic, this moisture permeates into the paper, altering its physical properties.

The goal of this study was to develop and validate a model capable of accurately describing the condensation and moisture transport phenomena within a paper cup. To begin, the key variables and functions of the system were identified and formalized into equations. These equations were then simulated using COMSOL Multiphysics software, which allowed for a precise and detailed representation of the physical processes involved. The model's validity was further ensured by comparing its predictions with experimental data, including temperature, humidity, and water content measurements collected during the experiments.

Through this research, it was concluded that the transport phenomena and vapor condensation within the pores of the paper cup are closely linked to external environmental conditions. Specifically, as external temperature and relative humidity increase, the driving force for condensation becomes stronger. When the temperature of the surroundings approaches that of the liquid inside the cup, and the

material contains a certain amount of water vapor under favourable conditions, condensation begins to occur within the material itself.

It is important to emphasize that even when the liquid diffusivity is not considered, a portion of the vapor inside the material still condenses, albeit in minimal amounts. The primary driving force is generated by the liquid penetrating the material, but it is essential to also account for the fraction of vapor that condenses and is already in equilibrium within the material.

Therefore, it is essential to consider not only the external condensation on the surface of the cup but also the internal condensation of water vapor that occurs within the material. This internal condensation plays a crucial role in the overall moisture dynamics and contributes to the material's performance and durability.

In summary, this study highlights the importance of understanding the interaction between the material and the surrounding environment. It emphasizes that both external and internal condensation mechanisms must be considered to fully grasp the moisture transport and condensation behavior in paper cups. Future research could focus on refining the model to better predict these phenomena under varying environmental conditions and further optimize the material properties for improved performance.

References

1. Benson, R. *Food packaging process: Balancing innovation with marketplace dynamics*. Available from: https://www.crbgroup.com/insights/food-beverage/food-packaging-process.
2. Silva, N. and H. Pålsson, *Industrial packaging and its impact on sustainability and circular economy: A systematic literature review.* Journal of Cleaner Production, 2022. **333**: p. 130165.
3. Anand, K., et al., *A tasty solution to packaging waste? Life cycle assessment of edible coffee cups.* Resources, Conservation and Recycling, 2024. **201**: p. 107320.
4. Simantiris, N., *Single-use plastic or paper products? A dilemma that requires societal change.* Cleaner Waste Systems, 2024. **7**: p. 100128.
5. Hashem, S. *Research Finds Half of Single-Use Plastic Waste is Produced by 20 Companies*. Available from: https://eponline.com/articles/2021/06/08/research-finds-half-of-singleuse-plastic-waste-is-produced-by-20-companies.aspx.
6. Commission, E. *Single-use plastics*. Available from: https://environment.ec.europa.eu/topics/plastics/single-use-plastics_en.
7. Triantafillopoulos, N. and A.A. Koukoulas, *The future of single-use paper coffee cups: Current progress and outlook.* BioResources, 2020. **15**(3): p. 7260.
8. Kirwan, M.J., *Paper and paperboard packaging.* Food and beverage packaging technology, 2011: p. 213-250.
9. Hubbe, M.A., *Paper's resistance to wetting–A review of internal sizing chemicals and their effects.* BioResources, 2007. **2**(1): p. 106-145.

10. Mokhothu, T.H. and M.J. John, *Review on hygroscopic aging of cellulose fibres and their biocomposites.* Carbohydrate Polymers, 2015. **131**: p. 337-354.
11. Foss, W.R., C.A. Bronkhorst, and K.A. Bennett, *Simultaneous heat and mass transport in paper sheets during moisture sorption from humid air.* International Journal of Heat and Mass Transfer, 2003. **46**(15): p. 2875-2886.
12. Faghri, A. and Y. Zhang, *Transport phenomena in multiphase systems*. 2006: Elsevier.
13. Bird, R.B., W.E. Stewai, and E.N. Lightfoot, *Phenomena Second Edition.*
14. Ramarao, B., et al., *Moisture diffusion inside paper materials in the hygroscopic range and characteristics of diffusivity parameters.* Drying technology, 2003. **21**(10): p. 2007-2056.
15. 6.1, C., *Heat Transfer Module*.
16. Ramarao, B. and S. Chatterjee. *Moisture sorption by paper materials under varying humidity conditions*. in *Transaction of 11th Fundamental Research Symposium Cambridge, UK*. 1997.
17. Parker, M., J. Bronlund, and A. Mawson, *Moisture sorption isotherms for paper and paperboard in food chain conditions.* Packaging Technology and Science: An International Journal, 2006. **19**(4): p. 193-209.
18. Monteith, M.U.J.I., *Principles of Environmental Physics*. 1990.
19. Hu, Y.-P., et al., *Experimental Study of the Anisotropic Thermal Conductivity of Spruce Wood.* International Journal of Thermophysics, 2023. **44**(8): p. 131.
20. Aslannejad, H. and S.M. Hassanizadeh, *Study of Hydraulic Properties of Uncoated Paper: Image Analysis and Pore-Scale Modeling.* Transport in Porous Media, 2017. **120**(1): p. 67-81.
21. Shi, K. and J. Yang, *Analysis and Solution of Condensation Phenomenon in Ring Main Unit.* E3S Web of Conferences, 2021. **290**: p. 03005.

Acknowledgement

I want to express my heartfelt gratitude to Prof. Anette Larsson for her unwavering belief in me, her kindness, and her willingness to engage. Thanks to her, I explored a new culture and gained a fresh perspective beyond my daily life in Italy. I deeply cherish our project discussions, especially during lunches or ice cream breaks amidst her busy schedules. Thank you for everything.

Un doveroso ringraziamento al Prof. Gaetano Lamberti, per aver indotto in me la voglia di approfondire la materia, di migliorare me stessa e per essere stato disponibile e professionale sempre nei miei confronti.

Ringrazio infinitamente il Prof. Diego Caccavo e la Dott. Raffaella De Piano che mi hanno insegnato tanto, soprattutto come migliorare a livello professionale, guidandomi in questo percorso turbolento e lungo.

Un grazie immenso va ai miei genitori, due persone profondamente diverse: uno più taciturno, l'altro pieno di energia; uno che preferisce non chiedere, l'altro che a volte chiede troppo. In entrambi mi rivedo moltissimo. Nonostante i conflitti e la testardaggine che ci accomuna, abbiamo sempre trovato il modo, alla fine, di capirci. Non siamo molto affettuosi tra noi, ma saremmo pronti a spaccare il mondo pur di difenderci a vicenda. Mi avete insegnato il valore del Rispetto e dell'Equità. Grazie perché, se oggi sono la Donna che sono, una donna che avanza sempre e sa quello che vuole, è anche grazie a voi, vi voglio un bene dell'anima (anche se non ve lo dico mai)!

Ringrazio i miei fratelli, Francesco e Giorgia, due persone molto diverse ma, al tempo stesso, incredibilmente simili a me. Ci lega il sangue, ma soprattutto un amore immenso, anche se raramente espresso a parole. Lo dimostriamo in altri modi. Ho sempre avuto lo sguardo su di voi, anche se forse non ve ne siete accorti, e sono profondamente orgogliosa dell'Uomo e della Donna che siete diventati. Ogni giorno mi insegnate qualcosa di nuovo e prezioso. Vi voglio un bene infinito.

Ringrazio i miei nonni, che mi hanno insegnato tanto, soprattutto il grande valore della famiglia e l'importanza di essere sempre orgogliosi di ciò che si fa. Anche se oggi uno di voi non è più con me, il tuo amore, Nonna, è sempre presente. Le tue parole dolci e amorevoli risuonano nella mia mente, e i tuoi occhi, al tempo stesso teneri e severi, saranno per sempre il mio faro. Mia omonima, mi manchi e ci manchi profondamente!