UNIVERSITI PUTRA MALAYSIA

REVISION OF MATHEMATICAL BASIS FOR THE HYPHOID CURVE

VIJAYALETCHUMY A/P ELUMALI

FS 2018 44

REVISION OF MATHEMATICAL BASIS FOR THE HYPHOID CURVE

By

VIJAYALETCHUMY A/P ELUMALI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

October 2017

DEDICATIONS

My Mother Ramai A/P Mabu

&

My Fiancè Darvindran A/L Rajgndran

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

REVISION OF MATHEMATICAL BASIS FOR THE HYPHOID CURVE

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VIJAYALETCHUMY A/P ELUMALI

October 2017

Chairman : Mai Zurwatul Ahlam Binti Mohd Jaffar, PhD
Faculty : Science

Filamentous microorganisms, for example, fungi, experience polarized growth that the elongated filamentous shape stems from intense growth activity occurred at the tip apex. Subsequently, examination on the geometry of the tip apex associated with its growth reveals relationship between physiological and geometrical parameters theoretically. Evidently, such revelation can be seen through contributions of the hyphoid model where it is one of insightful breakthroughs for community of mathematical mycology. The model proposes that geometry of the tip shape is determined by interplay between amount of vesicles and speed of moving Spitzenkorper expressed mathematically as hyphoid equation. Here, we provide additional theoretical relationship focusing on small-angle approximation and Sandwich theorem as an attempt to revise some steps of the derivation of the hyphoid equation. Choosing the small-angle approximation is plausible as the model deals with forms with size in micrometer. While, geometrical setting for proving Sandwich theorem fits geometrical setting for hyphal growth. We further examined the hyphal growth by considering outline shape of Spitzenkorper resembling either circle or horizontal ellipse located within the tip apex. This examination involves solving systems of nonlinear equations where we sought to find center of Spitzenkorper that fits within the tip apex maximally. Next, we proposed a hyphal growth model from the wall-elastic in which it was inspired by previous studies of elastic-wall profile of filamentous microorganisms. Also, we proposed actual coordinate where the wall elasticity collapses completely. Finally, we modeled an ideal filamentous microorganism excluding its growth mechanism and its tip range served as predictive tool for cell-profiling based on microscopic images for laboratory.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

PENYEMAKAN LENGKUNGAN HYPHOID BERDASARKAN ASAS MATEMATIK

Oleh

VIJAYALETCHUMY A/P ELUMALI

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Mikroorganisma berfilamen, sebagai contohnya, kulat mengalami pertumbuhan polarisasi yang bentuk filamen memanjang berasal dari aktiviti pertumbuhan yang kuat berlaku pada puncak tip. Selanjutnya, pemeriksaan geometri puncak tip yang dikaitkan dengan pertumbuhannya menunjukkan hubungan antara parameter fisiologi dan geometri secara teori. Jelasnya, pendedahan sedemikian boleh dilihat menerusi sumbangan hyphoid model di mana ia merupakan salah satu kejayaan yang membanggakan bagi komuniti mikologi matematik. Model ini mencadangkan geometri bentuk tip ditentukan oleh interaksi antara jumlah vesikel dan kelajuan pergerakan Spitzenkorper dinyatakan secara matematik sebagai persamaan hyphoid. Di sini, kami menyediakan hubungan teoretikal tambahan yang memberi tumpuan kepada pengiraan sudut kecil dan teorem Sandwich sebagai percubaan untuk mengubah beberapa langkah derivasi persamaan hyphoid. Memilih penghampiran sudut kecil adalah wajar kerana model berkenaan dibentuk dengan saiz dalam mikrometer. Sementara itu, persekitaran geometri untuk membuktikan teorem Sandwich sesuai dengan keadaan geometri untuk pertumbuhan hifa. Selanjutnya, kami mengkaji pertumbuhan hifa dengan mempertimbangkan bentuk garis kasar Spitzenkorper yang menyerupai sama ada bulat atau elips mengufuk yang terletak di puncak tip. Kajian ini melibatkan penyelesaian sistem persamaan tak linear di mana kita mencari pusat Spitzenkorper yang sesuai di dalam puncak tip secara maksimum. Seterusnya, kami mencadangkan satu model pertumbuhan hifa dari keanjalan dinding di mana ia diinspirasikan oleh kajian sebelumnya iaitu profil keanjalan dinding mikroorganisma filamen. Juga, kami mencadangkan koordinat sebenar di mana keanjalan dinding runtuh sepenuhnya. Akhirnya, kami memodelkan mikroorganisma filamen yang sesuai tidak termasuk mekanisme pertumbuhannya dan julat tipnya berfungsi sebagai alat ramalan untuk profil sel berdasarkan imej mikroskopik di makmal.

ACKNOWLEDGEMENTS

First of all praise to God with guidance and blessing from our god, finally I can finish my research work. I hereby would like to thank all of people who directly or indirectly involves in this research programme whom give a lots of valuable information to me in finishing this research work.

Initially, I would like to thank my supervisor Dr. Mai Zurwatul Ahlam Binti Mohd Jaffar who giving me an opportunity to enhance my skills and develops my knowledge in mathematical biology field throughout this research work. Once again, my grateful thanks goes to my helpful supervisor, for the supervision and support that she gave which truly help the progression and smoothness of this programme.

Besides that, I am also would like to express my gratitude to my lovely family members for the supportive along this research period especially my mother Madam Ramai and my brother Mr. Sarawanan. Overall, this research work would be one of the most memorable and unforgettable memory in my life.

I certify that a Thesis Examination Committee has met on 23 October 2017 to conduct the final examination of Vijayaletchumy a/p Elumali on her thesis entitled "Revision of Mathematical Basis for the Hyphoid Curve" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

This chapter focuses on filamentous fungi in terms of biological overview. That is, the structure of filamentous fungi and their functions as they relate to the growth habit. Following that, the growth mechanism of filamentous fungi are discussed. Apart from that, we presented objective of the study, problem statement and other basic concepts useful in understanding the study background of the research.

1.1.1 Biological Overview of Filamentous Fungi

Filamentous fungi are eukaryotic and heterotrophic microorganisms. These organisms are classified under a kingdom of Fungi which is discrete from plants, animals, protists and bacteria. These fungi are consist of various membrane-bounded subcellular compartments which are the sites of specialized functions.

1.1.1.1 Hypha

A hypha is a single filament of fungi and its body is divided into the apical and subapical region . The apical region is soft, elastic and the apex of the tip is the main place for construction of new cell wall. While the subapical region is rigid and no activity of growth takes place. As the tip continually extends, the more distal sections of the hyphal wall become rigid. This results in a steadily propagating finger-like structure that can grow up to 50-100 μm long (Goriely & Tabor, 2008).

1.1.1.2 Organelles

Filamentous fungi have a clear nucleus and membrane-bound organelles which are described as follows and also shown in Figure 1.1.

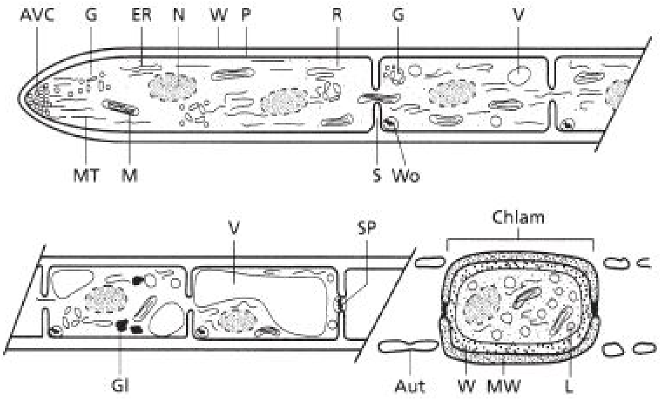

Figure 1.1: Polarized Growth of Hypha which is redrawn
(Source : Cole (1996))

(i) Nucleus

- Generally, the nucleus is the well-known organelle found in filamentous fungi, and in some species like *Basidiobolus ranarum* and *Erynia neoaphidis* (Gow & Gadd, 2007). The majority of the filamentous fungi have nuclei with diameters commonly in the range 1-3 μm. Generally, the nuclei of most eukaryotes are 3-10 μm in diameter which is bigger than the nuclei of filamentous fungi. The fungal nucleus is consist of the intensely electron-dense nucleolus, nucleopores and nucleoplasm without ribosome which is bounded by a double bilayer membrane. The shape of a fungal nucleus is roughly spherical especially in the extension of the regions close to the tips of narrow hyphae such as *Penicillium chrysogenum, Aspergillus giganteus* and *Aspergillus nidulans* (Gow & Gadd, 2007). The shape of nuclei of these hyphae is changed from an oval to prolonged parallel to the hyphal axis and after that a shape which is supposedly from an adaptation to the hyphal growth habit. The function of nucleus here are act as a storage of the cell hereditary material. It also maintains activities of the cell that including growth, intermediary metabolism, protein synthesis and reproduction (Gow & Gadd, 2007).

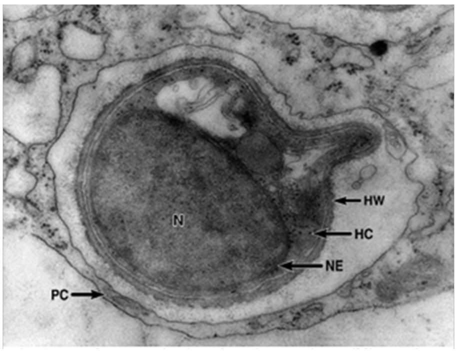

Figure 1.2: Diagrammatic Representation of Electron Micrograph Showing the Nucleus (N), Nuclear Envelope (NE), Cytoplasm (HC) and Cell Wall (HW) of a Fungal Hypha

(ii) The Endomembrane System

- The endomembrane system is a series of compartments that work together to package, label, and ship proteins and molecules. These systems comprise of the endoplasmic reticulum and the golgi apparatus (Deacon, 2013).

  (a) Endoplasmic Reticulum (ER)

  - ER is a broad membrane network of cisternae, which are held together by the cytoskeleton. It also visible to be closely linked in direct physical contact with the numerous other organelle membranes like vacuoles (Gow & Gadd, 2007). Although, the endomembrane system is discontinuous in most cases such that organelles are isolated within the cytoplasm. But, it still kept in dynamic contact with other organelles by the continuous traffic of cytoplasmic vesicles which flows between them. Rough ER and smooth ER are two basic types of ER that differ in both structures. Rough ER is a series of flattened sacs, covered with ribosomes and synthesizes proteins. While, smooth ER is a tubule network and lacks ribosomes which are responsible for synthesizes lipids, carbohydrates and steroids, maintains calcium concentration and drug detoxification.

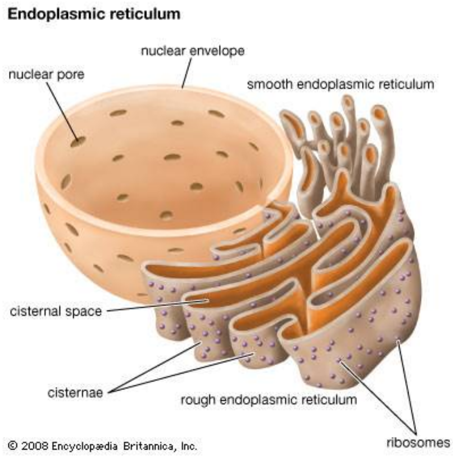

Figure 1.3: Structure of Rough ER and Smooth ER

(b) Golgi Apparatus

- A membrane-bound organelle with a single membrane is known as a golgi apparatus. It is mainly responsible for modifying, sorting and packaging the macromolecules such as proteins and lipids that are synthesized by the cell. In addition, it aids in the transportation of lipids throughout the cell and the formation of lysosomes. In most of the eukaryotes, Golgi apparatus is recognized as a stack of flattened lamellae in close connection and frequently enclosed by a cloud of vesicles in an active cell. This structure is known as a dictyosome which is rarely found in filamentous fungi, even though it happens in many members of the *Mastigomycetes* (Gow & Gadd, 2007). However, it is absent from species belonging to the order *Blastocladiales* in the class *Chytridiomycetes* (Gow & Gadd, 2007). However, different Golgi equivalents were identified in species belonging to the order Blastocladiales like *Allomyces macrogynus*, where they were composed of individuals cisternae (Gow & Gadd, 2007). It looks as usual of the majority of fungi, in where the Golgi apparatus takes place as isolated cisternae which are possibly difficult to distinguish from the endoplasmic reticulum. However, in many similar species of Golgi can be differentiated since they form loose but recognizable relations of small cisternae and broader lumen than the endoplasmic reticulum.

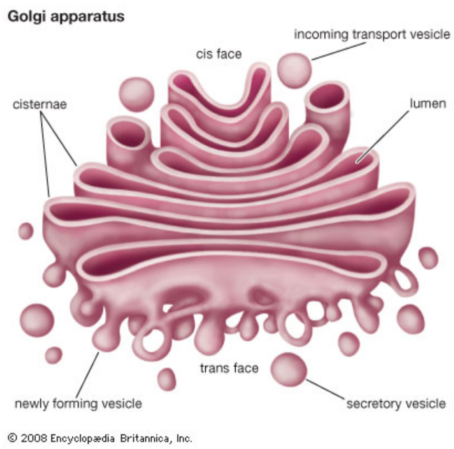

Figure 1.4: Structure of Golgi Apparatus

(iii) Mitochondria

- Mitochondria are membrane-bounded organelle with a double bilayer at where these membranes are composed of phospholipids and proteins. The filamentous fungi mitochondria are an exceptionally elongated shape in which they adopt in numerous species. Their internal membrane usually looks like the arrangement of lamella that lies parallel to each other and to the long axis of the organelle (Gow & Gadd, 2007). The extension in filamentous fungi is more significantly so that single mitochondria may extend 15μm or more along a hyphae (Gow & Gadd, 2007). Mitochondria are called as the power centers of the cell since it produces the energy a cell needs to distribute and produce secretory products.

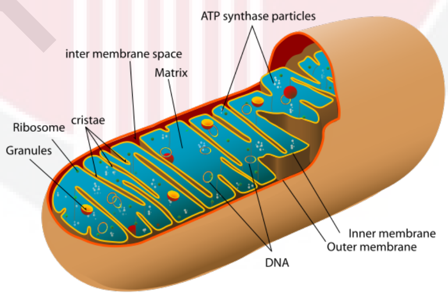

Figure 1.5: Structure of Mitochondria

(iv) Vesicles

- Vesicles are the smallest organelles and present most abundantly in filamentous fungi. In general, vesicles are noticeable as a dense cluster in the hyphal apex even though they take place in lower concentrations all over the cytoplasm. These reflect their important role as transport organelles mediating a significant proportion of the cellular traffic in both structural and enzymic proteins and many other cellular components, particularly lipids and polysaccharides.

Localized accumulations of vesicles may occur during the mycelium, often associated with actual or incipient wall-formation. As such, they often appear at the forming edges of septa or on the side wall of hyphae or spores prior to the establishment of a branch or germ tube. Vesicle collection also sometimes found in the angle between the septum and the wall next to maturity of hyphae. This may indicate a role of these cross walls in preventing the flow of vesicles along the hyphae, resulting in a localized concentration of vesicles as a first step towards a new branch in that region (Gow & Gadd, 2007).

(v) Vacuoles

- In the older regions of hyphae, the structure of vacuoles frequently is seen as rounded. However, recent studies have been proved that the vacuoles are also in the tubular structure expanding into the tip cells (Deacon, 2013). It plays many important roles that include the storage and recycling of cellular metabolites. For instance, the vacuoles of some fungi which includes mycorrhizal species collect phosphates in the polyphosphate form. Vacuoles also act as a storage of calcium and regulate cellular pH. In addition, vacuoles contain proteases which are responsible for breakdown of cellular proteins and recycling of the amino acids. All these roles are important in cell extension and in driving the protoplasm advances as the extension of the hyphae at the tips.

(vi) Microbodies

- Microbodies are single bilayer bounding membrane that consists of simple electron-dense cytoplasmic inclusions either in spherical or ovoid with diameter 0.1-2.0 μm (Beckett et al., 1974). Occasionally, it comprises an electron dense inclusion (Gow & Gadd, 2007). Recent studies shows that microbody only consist of peroxisomes and glyoxysomes except for hydrogenosomes, lysosomes and woronin bodies(Carson & Cooney, 1990; Maxwell et al., 1977). These organelles are mainly responsible for deploying the complex carbon which consists of polymers of the plant host cell walls, especially in necrotrophic plant-pathogenic fungi (Maxwell et al., 1977). Apart from that, it also considered to function as mobilizing lipid-reserves during spore germination (Maxwell et al., 1977). On the other hand, it is also considered engaged in lipid biosynthesis for storage during sporulation and as well in the development of spore like melanogenesis (Maxwell et al., 1977).

(vii) Hydrogenosomes

- Recently, hydrogenosomes are membrane bound organelles that have been discovered in a very restricted number of species of fungi (Gow & Gadd, 2007). The fungus itself is very uncommon since they are obligately anaerobic which took place in the herbivores rumen and just tenuously be believed filamentous fungi due to they result in rhizoids instead of hyphae and seems to belong to the class Chytridiomycetes. It frees the hydrogen molecule (H_2) as a by-product of energy generation under anaerobic conditions (Carlile et al., 2001).

(viii) Woronin Bodies

- The woronin bodies are called as small cytoplasmic particles (Buller,1933). It could be the most vital of the organelles which observed only in the filamentous fungi. The features of the ascomycetes and of the deuteromycetes which associated to ascomycete cause the woronin bodies happen in the most of the species (Markham & Collinge, 1987).

(ix) The Cytoskeleton

- A series of intracellular proteins that maintain the internal structure of cell is known as cytoskeleton (Deacon, 2013). It has three main protein filaments which are actin filaments, microtubules and intermediate filaments. The cytoskeleton mediates movement by helping the cell move in its environment and mediating the movement of the cell's components (Deacon, 2013).

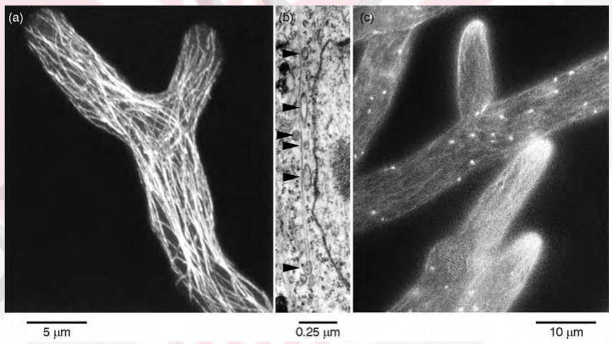

Figure 1.6: Representaion of Cytoskeleton into (a) Actin Filaments, (b) Microtubules and (c) Intermediate Filaments

(x) The Cell Membrane

- Fungal cell membrane is made up of two layers of phospholipids and embedded with proteins. The membrane also can anchor some enzymes, mainly chitin synthase and glucan synthase (Deacon, 2013). The cell membrane is mainly responsible for protecting the integrity of the interior of the cell with the movement of certain substances in and out of the cell (Deacon, 2013).

(xi) Cell Wall

- Cell wall of fungi lacks cellulose and there are no chloroplasts. Apparently, it is composed of chitin, glucans and proteins. It protects the hyphae from bursting in a hypotonic medium. It also regulates the rate and orientation of cell growth and maintains the cell volume (Kavanagh, 2011).

(xii) Septum

- Along the length of most hyphae cells, septa are found at fairly regular intervals in order to prevent the accidental loss of cell organelles between hyphal compartments (Gow & Gadd, 2007). A woronin body quickly seals the septal pores to restrict the damage if the part of the hypha is damaged (Carlile et al., 2001). Following that, at the back of damaged compartment, the hypha can grow back into a newly formed tip. *Ascomycetes* and *Basidiomycetes* have non-complex septa and more complex dolipore septum with respectively whereas *Oomycetes* deficient in septa (Deacon, 2013).

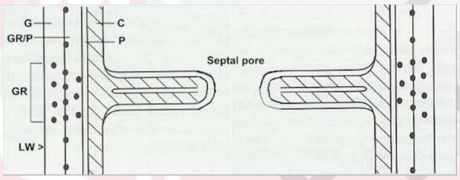

Figure 1.7: The Diagram shows a Simple Septum of Neurospora Crassa that includes the Lateral Wall (LW) of the Hypha, a Proliferation of the Glycoprotein Reticulum (GR), Glucan Layer (G), Glycoprotein Reticulum embedded in Protein (GR/P), Protein (P) and Chitin (C)

(Source : Deacon, 2013)

(xiii) Spitzenkorper

- The Spitzenkorper is a specialized organelle in fungi which is responsible for hyphal morphogenesis polarity. Its location is in the extreme apex of growing hyphae and visually apparent as a spherical phase dark region under the phase contrast microscopy. This structure apparent only in higher fungi that include ascomycetes, deuteromycetes and basidiomycetes. A very clear explanation about Spitzenkorper is explained in Chapter 4.

1.1.1.3 Life Cycle of Filamentous Fungi

The life cycles of *Aspergillus nidulans* in both sexual and asexual reproduction is described. During the asexual reproduction in *Aspergillus nidulans*, single nucleus contained by spores sprout into multinucleate, homokaryotic hyphae. For a timeframe, hyphae develop and branch and after that begins a particular branch known as the conidiophore. An assortment of various cell sorts required in the advancement conidiophore and considered as a model development process. In conidiophore, the nucleus separates mitotically and produces haploid conidia. Upon discharge, conidia sprout into vegetative hyphae developing, and the cycle proceeds. In *Aspergillus nidulans*, the elements that required in the advancement of early conidiophore are vague, but it involves the supply of carbon and nitrogen. This generally just happen in a culture grown on solid media with air interphase instead of in the liquid.

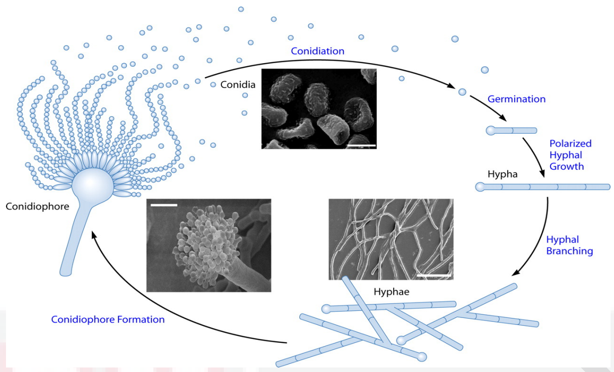

Figure 1.8: Life Cycle of Filamentous Fungi
(Source : Shapiro et al., 2011)

During sexual reproduction in *Aspergillus nidulans*, vegetative hyphae germinate and combine to produce hyphae dikaryotic. The dikaryotic hyphae separate into a creating fruiting body, cleistothecia which made out of numerous cell sorts, for example, sterile and fertile hyphae. Within the cleistothecium, the dikaryotic fertile hyphae develop into croziers, which then separate into creating asci. Inside the crozier, nuclear fusion takes place and produces a diploid. This diploid experiences meiosis with quickly prompts four meiotic products and afterward these products experience mitosis produces eight haploid ascospores. A further round of mitosis experienced by ascospores leads them binucleate. In a cleistothecium, a large number of asci are contained and are delicate, deter their individual isolation. At the time of discharge, ascospores grow into hyphae. *Aspergillus* is self-fertile, and sexual reproduction can be started inside one colony containing genetically indistinguishable nuclei. Without the formation of the heterokaryon with other strain, the single strain separates a cleistothecium into a crozier and ascogenous hypha.

1.2 Problem Statement

Tip growth is polarized, where its activity is concentrated at the tip of a filamentary microorganism resulted in elongated tubular shape. In 1989, Bartnicki-Garcia et al. proposed a hyphoid equation which relates the amount of exocytic vesicles released from Vesicle Supply Center (VSC) and VSC speed. However, in subsequent years, Koch (2001) questioned validity of some steps employed in the derivation. These steps have been revised by Jaffar (2012) but there is no further clarification linking mathematics with biology of the hyphal elongation. For this reason, we are concerned with providing a connection between mathematics and biology of the hyphal elongation. Furthermore, the two-dimensional outline shape of the Spitzenkorper which resembles either circle or horizontal ellipse. This motivates us to investigate the effect of the shape of Spitzenkorper on hyphal tip growth. In additon, a soft-spot hypothesis in tip-growing cells is modeled by a function known as the effective pressure profile requires information about tip radius, length of tip extension zone and turgor pressure (Goriely et al., 2010). For this reason, we develop a different perspective to construct a elastic hyphal apex wall model without knowing the apical length of the extension zone. Apart from that, Goriely et al. (2005) proposed a geometric model that relates tip monotonicity with curvature, κ, is κ^p, where $p \geq 1$. In following years, Jaffar & Davidson (2013) suggested that $p > 0$ also results in a monotonically increasing function of κ. This motivates us to find the derivation of shape equation of an ideal filamentous cell excluding its growth mechanism.

1.3 Objectives of the Study

The objectives of the research work are:

1. To establish additional theoretical relationship between physiological and geometrical parameters of the hyphal tip through the small angle approximation and Sandwich theorem as an attempt of revising some steps of derivation of the hyphoid equation.

2. To examine centers of different outline-shapes of the Spitzenkorper inscribed in the tip apex where the outline-shapes occupy the tip apex maximally.

3. To model the hyphal-growth profile based on wall-elasticity. Previously, such a profile was modeled by collecting actual laboratory data. Here, it is adaptation of Hookes Law and Newtons Second Law of Motion. Besides that, computation of complete collapse of the wall-elasticity is included.

4. To model ideal filamentous microorganism without involvement of its growth mechanism followed by determination of its tip range where its goal is predicting cell-profiling given microscopic image.

1.4 Significance of the Study

The significance of this study are

(i) This study shows that the equality-condition employed by Jaffar (2012) is abstract equality due to the nonexistence of analytic solution. Its actual being is approximately equal and this condition is used to revise the hyphoid equation.

(ii) This study proposes relationships between growth and geometrical variables of the hyphoid equation which provides agreeable reflections of tip growth with Bartnicki-Garcia et al. (1989). These relationships are based on specific assumptions of β which offer a new insight of the narrower or broader hyphal tip.

(iii) The potential of these geometric relationships allows us to calculate arc length, the slope of secant line and slope of the tangent line on the tip growth in the laboratory. In other words, it can be used as a tool for analyzing experimental data for tip shapes.

(iv) The trend of the slopes of tangent lines along the tip can be served as a future perspective in modeling the tip growth geometrically.

(v) The two-dimensional outline shape of the Spitzenkorper allow us to predict the tip shapes either narrower or wider hyphal tip by using system of equations. It can be used as a tool for lab work in terms of profiling cell given a microscopic image.

(vi) This study proposes a different perspective that is looking at the elastic hyphal apex wall, position of x at time, t based on the Goriely et al. (2010) modelling. This offer a new insight of the occurrence of the nearest anti-elasticity wall without knowing the length of tip extension zone.

(vii) This study derives shape equation of an ideal filamentous cell based on slopes excluding its growth mechanism. It offers a comparative-predictive role for tip monotonicity profiling.

1.5 Scope of the study

This study focuses on the investigation of an essential feature of the condition. Note that Jaffar (2012) used curvature approach to derive the alternative derivation of the hyphoid equation associated with the equality-condition.

This research study also focuses on the relationship between the growth of actual fungi and geometrical variables that developed in this study. Furthermore, this study finds the relationship among the two-dimensional outline shape of the Spitzenkorper, hyphal tip growth and tip shape. Based on the Goriely et al. (2010) modelling, a different perspective that is looking at the elastic hyphal apex wall that developed in this study. Apart from that, the shape equation of an ideal filamentous cell excluding its growth mechanism was presented.

1.6 Overview of the Study

This thesis is organised as follows:

In this Chapter 1 we discussed the background of the research study; briefly discussed biological overview of filamentous fungi. We presented objective of the study, problem statement and other basic concepts useful in understanding the study area of the research. The mathematical overview of filamentous fungi is presented in Chapter 2 where a brief introduction of hyphoid model is given. The methodology of an alternative derivation of the hyphoid equation and its results will be discussed in Chapter 3. Apart from that, we also describe the effect of two-dimensional outline shape of the Spitzenkorper on hyphal tip growth and tip shape in Chapter 4. In addition, a different perspective modeling inspired by Goriely et al. (2010) will be discussed in Chapter 5. The derivation of the shape equation of an ideal filamentous cell based on slopes excluding its growth mechanism is presented in Chapter 6. The conclusions and future work are highlighted in Chapter 7.

1.7 Summary

In this chapter we discussed the background of the research study, briefly discussed the biological overview of filamentous fungi. That includes structure and growth mechanisms of the filamentous fungi, diseases of fungi in humans and plants and also the role of fungi. The problem statement, objectives, significance and scope of the study are presented in this chapter.

BIBLIOGRAPHY

Bartnicki-García, S. (2002). Hyphal tip growth: outstanding questions. *MYCOLOGY SERIES* 15 29–58.

Bartnicki-Garcia, S., Bartnicki, D. & Gierz, G. (1995a). Determinants of fungal cell wall morphology: the vesicle supply center. *Canadian journal of botany* 73 372–378.

Bartnicki-Garcia, S., Bartnicki, D. D., Gierz, G., López-Franco, R. & Bracker, C. E. (1995b). Evidence that spitzenkörper behavior determines the shape of a fungal hypha: a test of the hyphoid model. *Experimental mycology* 19 153–159.

Bartnicki-Garcia, S., Hergert, F. & Gierz, G. (1989). Computer simulation of fungal morphogenesis and the mathematical basis for hyphal (tip) growth. *Protoplasma* 153 46–57.

Beckett, A., Heath, I. B., McLaughlin, D. J. et al. (1974). An atlas of fungal ultrastructure. *An atlas of fungal ultrastructure.* .

Boswell, G. P., Jacobs, H., Ritz, K., Gadd, G. M. & Davidson, F. A. (2007). The development of fungal networks in complex environments. *Bulletin of Mathematical Biology* 69 605.

Carlile, M. J., Watkinson, S. C. & Gooday, G. W. (2001). *The fungi.* Gulf Professional Publishing.

Carson, D. B. & Cooney, J. J. (1990). Microbodies in fungi: a review. *Journal of industrial microbiology* 6 1–18.

Castle, E. S. (1958). The topography of tip growth in a plant cell. *The Journal of general physiology* 41 913–926.

Cole, G. (1996). Basic biology of fungi .

Davidson, F. A. (2007). Mathematical modelling of mycelia: a question of scale. *Fungal Biology Reviews* 21 30–41.

Deacon, J. W. (2013). *Fungal biology.* John Wiley & Sons.

Diéguez-Uribeondo, J., Gierz, G. & Bartnicki-Garcia, S. (2004). Image analysis of hyphal morphogenesis in saprolegniaceae (oomycetes). *Fungal Genetics and Biology* 41 293–307.

Edwards, C. (2012). *Advanced Calculus of Several Variables.* Dover Books on Mathematics. Dover Publications. URL https://books.google.com.my/books?id=sZIFcJ8DJAIC.

Fisher, K., Lowry, D. & Roberson, R. W. (2000). Cytoplasmic cleavage in living zoosporangia of allomyces macrogynus. *Journal of microscopy* 198 260–269.

Flärdh, K. (2003). Growth polarity and cell division in streptomyces. *Current opinion in microbiology* 6 564–571.

Gierz, G. & Bartnicki-Garcia, S. (2001). A three-dimensional model of fungal morphogenesis based on the vesicle supply center concept. *Journal of Theoretical Biology* 208 151–164.

Goriely, A., Károlyi, G. & Tabor, M. (2005). Growth induced curve dynamics for filamentary micro-organisms. *Journal of mathematical biology* 51 355–366.

Goriely, A. & Tabor, M. (2003a). Biomechanical models of hyphal growth in actinomycetes. *Journal of theoretical biology* 222 211–218.

Goriely, A. & Tabor, M. (2003b). Self-similar tip growth in filamentary organisms. *Physical review letters* 90 108101.

Goriely, A. & Tabor, M. (2008). Mathematical modeling of hyphal tip growth. *Fungal Biology Reviews* 22 77–83.

Goriely, A., Tabor, M. & Tongen, A. (2010). A morpho-elastic model of hyphal tip growth in filamentous organisms. In *IUTAM Symposium on Cellular, Molecular and Tissue Mechanics*. Springer, 245–255.

Gow, N. & Gadd, G. (2007). *Growing Fungus*. Springer Netherlands. URL `https://books.google.com.my/books?id=9e0GCAAAQBAJ`.

Gray, D., Gooday, G. & Prosser, J. I. (1990). Apical hyphal extension in streptomyces coelicolor a3 (2). *Microbiology* 136 1077–1084.

Grove, S. N. & Bracker, C. E. (1970). Protoplasmic organization of hyphal tips among fungi: vesicles and spitzenkörper. *Journal of Bacteriology* 104 989–1009.

Hale, M. D. & Eaton, R. A. (1985). Oscillatory growth of fungal hyphae in wood cell walls. *Transactions of the British Mycological Society* 84 277–288.

Harold, F. (1997). How hyphae grow: morphogenesis explained? *Protoplasma* 197 137–147.

Harris, S. D. (2008). Branching of fungal hyphae: regulation, mechanisms and comparison with other branching systems. *Mycologia* 100 823–832.

Holbrow, C., Lloyd, J., Amato, J., Galvez, E. & Parks, M. (2010). *Modern Introductory Physics*. SpringerLink: Springer e-Books. Springer New York. URL `https://books.google.com.my/books?id=KLT\_FyQyimUC`.

Jaffar, M. & Davidson, F. (2013). Basic rules for polarised cell growth. *Journal of theoretical biology* 336 44–51.

Jaffar, M. M. (2012). *Mathematical models of hyphal tip growth*. Ph.D. thesis, University of Dundee.

Kavanagh, K. (2011). *Fungi: Biology and applications.* John Wiley & Sons.

Kline, M. (2013). *Calculus: An Intuitive and Physical Approach (Second Edition).* Dover Books on Mathematics. Dover Publications. URL https://books.google.com.my/books?id=tZy8AQAAQBAJ.

Koch, A. (2001). *Bacterial growth and form.* Springer Science & Business Media.

Koch, A. L. (1982). The shape of the hyphal tips of fungi. *Microbiology* 128 947–951.

Koch, A. L. (1983). The surface stress theory of microbial morphogenesis. In *Advances in microbial physiology*, vol. 24. Elsevier, 301–366.

Koch, A. L. (1994). The problem of hyphal growth in streptomycetes and fungi. *Journal of theoretical biology* 171 137–150.

Köhli, M., Galati, V., Boudier, K., Roberson, R. W. & Philippsen, P. (2008). Growth-speed-correlated localization of exocyst and polarisome components in growth zones of ashbya gossypii hyphal tips. *Journal of cell science* 121 3878–3889.

Larson, R. (2012). *Brief Calculus: An Applied Approach.* Cengage Learning. URL https://books.google.com.my/books?id=jrVezRRGymAC.

Larson, R. & Edwards, B. (2009). *Calculus.* Cengage Learning. URL https://books.google.com.my/books?id=Xn9rXyPSrzAC.

LaTorre, D., Kenelly, J., Reed, I., Carpenter, L. & Harris, C. (2011). *Calculus Concepts: An Informal Approach to the Mathematics of Change.* Cengage Learning. URL https://books.google.com.my/books?id=1Ebu2Tij4QsC.

Markham, P. & Collinge, A. J. (1987). Woronin bodies of filamentous fungi. *FEMS Microbiology Reviews* 3 1–11.

Maxwell, D., Armentrout, V. & Graves Jr, L. (1977). Microbodies in plant pathogenic fungi. *Annual review of phytopathology* 15 119–134.

Prosser, J. I. & Tough, A. (1991). Growth mechanisms and growth kinetics of filamentous microorganisms. *Critical reviews in biotechnology* 10 253–274.

Protter, M. & Protter, P. (1988). *Calculus with Analytic Geometry.* Jones and Bartlett. URL https://books.google.com.my/books?id=jTmuOwwGDwoC.

Read, N. D. & Steinberg, G. (2008). Editorial. *Fungal Biology Reviews* 22 43. Hyphal Tip Growth, URL http://www.sciencedirect.com/science/article/pii/S1749461308000225.

Riquelme, M. & Bartnicki-Garcia, S. (2004). Key differences between lateral and apical branching in hyphae of neurospora crassa. *Fungal Genetics and Biology* 41 842–851.

Riquelme, M., Gierz, G. & Bartnicki-Garcia, S. (2000). Dynein and dynactin deficiencies affect the formation and function of the spitzenkörper and distort hyphal morphogenesis of neurospora crassa. *Microbiology* 146 1743–1752.

Saunders, P. & Trinci, A. (1979). Determination of tip shape in fungal hyphae. *Microbiology* 110 469–473.

Shapiro, R. S., Robbins, N. & Cowen, L. E. (2011). Regulatory circuitry governing fungal development, drug resistance, and disease. *Microbiology and Molecular Biology Reviews* 75 213–267.

Smith, R. & Minton, R. (2007). *Calculus: Early Transcendental Functions*. McGraw-Hill Higher Education.

Sugden, K., Evans, M., Poon, W. & Read, N. (2007). Model of hyphal tip growth involving microtubule-based transport. *Physical Review E* 75 031909.

Trinci, A. & Banbury, G. (1967). A study of the growth of the tall conidiophores of aspergillus giganteus. *Transactions of the British Mycological Society* 50 525IN1–538.

Trinci, A. & Saunders, P. (1977). Tip growth of fungal hyphae. *Journal of General Microbiology* 103 243–248.

Vargas, M. M., Aronson, J. & Roberson, R. W. (1993). The cytoplasmic organization of hyphal tip cells in the fungusallomyces macrogynus. *Protoplasma* 176 43–52.

Zill, D. & Cullen, M. (2006). *Advanced Engineering Mathematics:*. No. v. 1 in Prindle, Weber & Schmidt Series in Advanced Mathematics. Jones and Bartlett Publishers. URL `https://books.google.com.my/books?id=x7uWk8lxVNYC`.

Zill, D. & Dewar, J. (2015). *Precalculus with Calculus Previews*. The Jones & Bartlett Learning Series in Mathematics. Jones & Bartlett Learning. URL `https://books.google.com.my/books?id=Ue8BCwAAQBAJ`.