

A CFD STUDY INVESTIGATING THE INFLUENCE OF BOTTOM BOARD
GEOMETRY ON PHYSICAL PROCESSES WITHIN A STANDARD
HONEYBEE HIVE

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ABSTRACT

A CFD STUDY INVESTIGATING THE INFLUENCE OF BOTTOM BOARD GEOMETRY ON PHYSICAL PROCESSES WITHIN A STANDARD HONEYBEE HIVE

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The influence of bottom board design on the honeybee hive environment was explored using computational fluid dynamics (CFD) analysis. Two design aspects were evaluated: in Experiment A the bottom board was replaced with a rectangular cavity of variable depth (δ) below the hive inlet; in Experiment B a shaped bottom cavity was added that was defined by the variable parameter α , to create a series of front-skewed and back-skewed bottom cavities. Adding a bottom cavity below the hive resulted in increased air exchange between the hive body and ambient environment. The nature of flow within the hive changed resulting in interesting flow patterns – most notably the formation of a vortex below the hive inlet. Bottom cavity shape influences the nature of flow within the hive body in subtle ways. The results of this study indicate that bottom board design can be optimized. Data gaps that exist in literature must be filled to refine the current hive model and develop a design optimization tool.

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This project would not have been possible without the generous support of many contributors:

This project was inspired by Andrew Serafin, and experienced beekeeper with a passion for science. His perception that a 'bowl-like' cavity beneath the hive entrance could offer benefits for honeybees provided the direction and structure of this research. Andrew also supplied an immense amount of his personal research material, representing both his time and extensive dedication to the subject.

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Professor Peter Kevan of the University of Guelph is responsible for initializing the project through his participation in the co-op education program at the University of Guelph. His initial interest in the nature of hive fluid dynamics provided a base-structure for this research, which eventually grew into an inter-disciplinary, inter-departmental collaboration between the School of Environmental Science, School of Engineering, Department of Mathematics and Statistics, and the Biophysics Interdepartmental Group of the University of Guelph. Peter successfully obtained additional

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Chapter 1

Introduction

1.1 The Importance of Honeybees

Bees are important insects which function as pollinators in Earth's terrestrial systems of plants and animals. By visiting many flowers bees, along with an assortment of other pollinators, actively exchange pollen between plants thereby increasing the frequency of successful pollination (which otherwise depends on wind, water and chance). Pollinators are drawn to flowers by the calorie rich products they contain. A pollinator arrives at a flower and, by contact, transfers pollen from other flowers, enabling fertilization of the plant. What makes honeybees unique is their habit of stock-piling the plant products they harvest. Honeybees warehouse nectar within their hive from which they evaporate excess moisture to produce honey. Beekeeping began as an effort to make honey collection feasible for humans and through history many versions of beehives have been documented. Nowadays beekeeping is a large commercial enterprise. Beekeepers not only generate hive products for sale, but also earn revenue by renting bees to crop-framers for pollination. In fact, modern agriculture relies heavily on commercial beekeepers, or apiculturists to sustain abundant crop yields. Trucks loaded with honeybees travel the continent delivering colonies

to flowering crops in order to generate the vast amounts of food needed to meet consumer demand. California almonds are a food-crop that is exclusively dependent on honeybees for pollination, which are imported every year in massive quantities to support a market worth \$2.2 billion (2006)[53]. By this measure, the labour of the honeybee provides not only the direct hive-products of honey, wax, pollen and propolis, but also supports agricultural industries worldwide (Value added to GDP by all sectors of agriculture in trillions of US dollars, 2007: China - \$376.3; India - \$213.2; USA \$183.2, World Bank Statistics).

Beekeeping has a long history as a commercial enterprise. From ancient Egyptian honey to Medieval mead the products collected by apiculturists have been enjoyed for millennia by consumers too timid to take up the practice themselves. Apiculture evolved alongside human society as new technologies and materials paved the way for improved tools and techniques. The most significant milestone for modern apiculture was the invention of the removable-frame beehive. This technology allowed the standardization and spread of commercial beekeeping world wide.

1.2 Background on Honeybee Hives

Honeybee colonies can exist as feral-bees living in nature or managed-bees living in engineered structures. In nature honeybees are typically found in hollow tree cavities, although they can also be found in other hollow bodies (caves, cliff faces, empty burrows etc.)[12], [41]. Honeybees select an enclosed cavity of appropriate volume wherein they construct wax combs in long sheets. Bees attach the wax comb sheets to the top and sides of the cavity, allowing them to hang over the bottom, while maintaining a comb-separation distance of roughly $\frac{3}{8}$ " - appropriately called bee-space. The combs are subdivided into thousands of cells featuring the familiar hexagonal shape associated with honeybee comb. Bees use the combs to house their incubating

larva (collectively referred to as the brood), to store of honey and pollen, and for various heating and cooling activities. The bee-space allows worker bees to travel over each comb surface and access every comb cell. The distribution of materials within the hive is well defined as illustrated in Figure 1.1. In both the natural and commercial hive setup the brood cells are positioned at the bottom of the combs near the hive inlet. Nectar is stored at the top of the nest and, as the liquid fraction is evaporated to produce honey, the storage cells are capped with wax and next row of cells lower is filled, causing the band of ripened honey to propagate downward. Stores of pollen are far less abundant than stores of honey, and are typically deposited in small collections of cells between the brood region and the honey region.

1.2.1 Natural hives

Research has shown that honeybees are very selective of their nesting sites[43]. Honeybees tend to select hollow tree cavities with single entrances located near the bottom of the cavity [3][41]. Several characteristics of the typical natural nest differ from those of the commercial standard. For example the natural nest has a vertically elongated profile and a circular cross-section. Inside a new nest site, honeybees construct wax combs starting at the top of their nest. To prepare the cavity, bees first use their bodies and legs to file-down any rough, rotted surfaces to uncover clean, solid material suitable for comb attachment[41]. Bees make a similar modification at the hive inlet where they file-down rough surfaces lining the inlet passageway and apply smoothed propolis. A mean depth of 15 cm is reported for inlet passageway before it meets the cavity [41] and the entrance diameter ranges from 20-40 cm[41],[12]. Although entrance position is relatively variable, feral colonies seem to have preference for cavities with a single hive entrance[41],[12]. Having a single entrance prevents displacement ventilation and may offer honeybees more control over their hive environment.

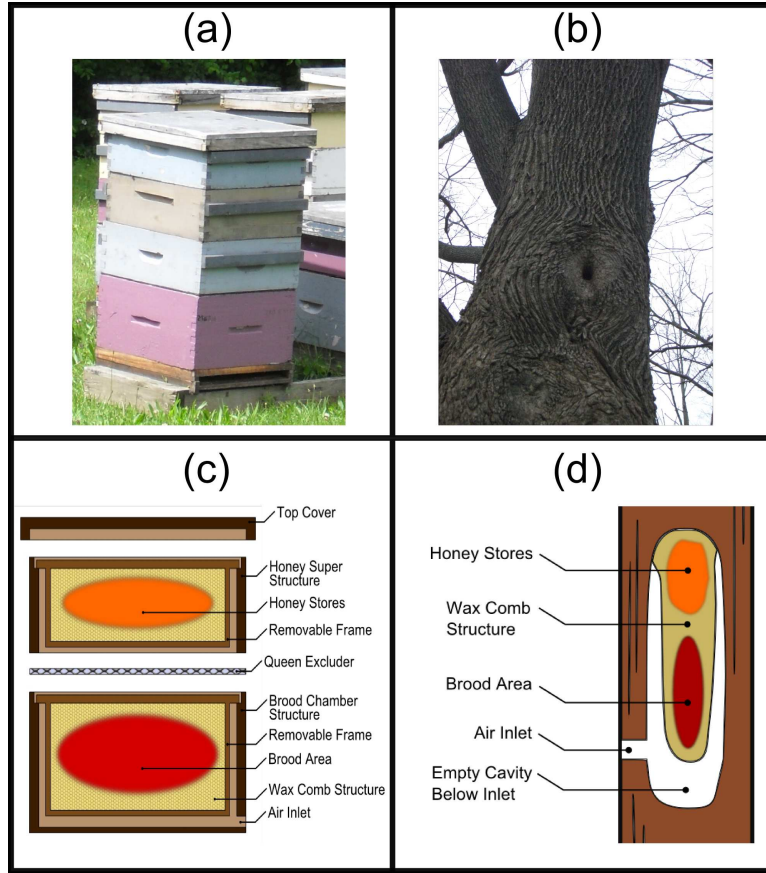


Figure 1.1: Comparison between the natural and commercial hive architecture: (a) photograph of working commercial hives in the field with various numbers of honey supers; (b) photograph of a large tree with a cavity (c) cross-section schematic diagram of a commercial hive with one honey super; (d) cross-section schematic diagram of a natural hive, figure adapted from diagram in a study of natural nests in the North Eastern US [41].

1.2.2 Commercial hives

Commercial honeybee hives, commonly known as Langstroth hives, have been standard since 1852. Patented in 1852 by Lorenzo Langstroth [24], the first modern beehive was designed to better accommodate beekeeping practices. The work of Langstroth was derived from removable-frame concepts developed by Polish and German bee researchers Dzierzon and Van Berlepoth [28]. The first beehive was designed to support the life of honeybees and facilitate manipulation of the hive for beekeepers. To facilitate discussion of the present study, an overview of the standard components

of a Langstroth hive is presented:

Removable frames: The ability to remove individual frames from the hive without much disruption to the rest of the colony is a key feature of the modern hive. Each frame supports a comb structure constructed by the bees using wax secreted from their bodies. The comb structures are used to store incubating brood, honey, and pollen as well as for heating and cooling activities. Each frame is initialized with a manufactured sheet of wax, called foundation, placed at the centre of the frame. This helps bees with comb construction while enforcing a uniform cell pattern. A bee is free to construct comb on both sides of the wax foundation. The end result is a two-sided comb-frame that is two cells thick. There are many sizes of frames typically used by beekeepers, however in our study we consider two: deep frames for the *brood chamber* and shallow frames for the *honey super*.

REMOVABLE FRAMES

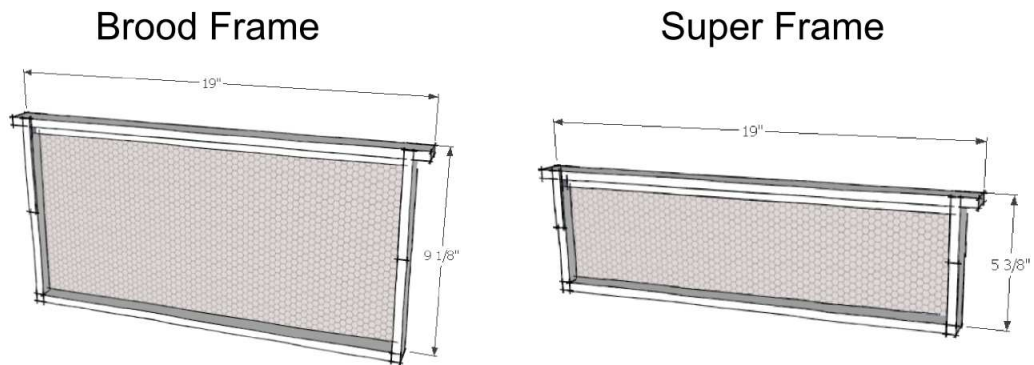


Figure 1.2: Standard removable comb frames are available in various sizes depending on their use. Brood chamber frames are deeper than honey super frames.

Brood chamber: The hive compartment which houses the brood of the colony is referred to as the brood chamber. It is the deepest hive compartment and is

the first to be stacked on top of the bottom board. A standard brood chamber supports 10 frames which rest upon notches at the top of the compartment such that frames run perpendicular to the inlet. In this way, the frames hang from the top of the chamber and maintain the appropriate beespace gap on all sides. The queen is restricted to this area of the hive where she performs her laying work and as a result, the frames of the brood chamber are covered in capped brood. The brood chamber is open at the top and bottom allowing for the flow of materials and bees through it.

BROOD CHAMBER

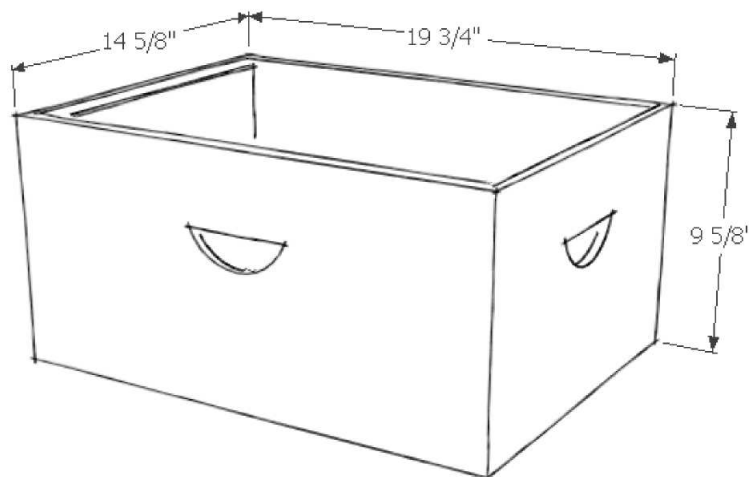


Figure 1.3: A standard brood chamber is a simple box open on the top and bottom faces. A small notch runs the span of the short sides of the box to support the comb frames.

Honey super: The collection of honey from honeybees is facilitated by the honey super compartment. The super consists of a hive box with the same length and width as the brood chamber but a shorter height. Honey supers are shallow to reduce the weight of the compartment when it is full of ripened honey. The super compartment is stacked on top of the brood chamber in groups of 2-

4 depending on the strength of the colony and time of year. Like the brood chamber, the honey super is open at the top and bottom to allow the flow of materials and bees through it. Empty supers are stacked on top of the brood chamber, effectively increasing storage capacity and the height of the hive. Full supers are removed from the top of the stack and empty ones are added to replace them.

HONEY SUPER

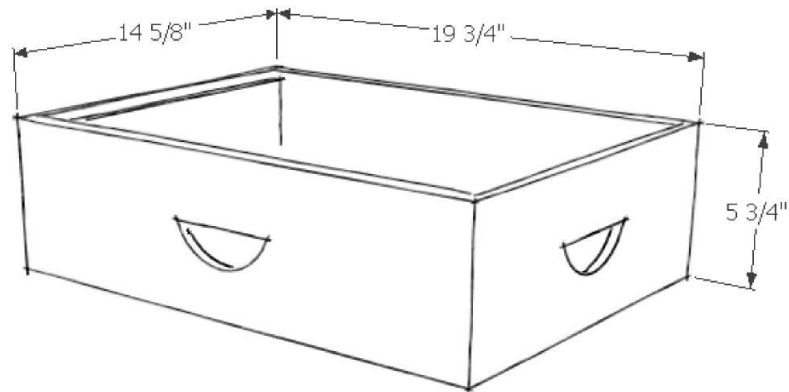


Figure 1.4: A standard honey super is a simple box having the same length and width as the brood chamber, but is considerably shorter.

Queen excluder: The queen excluder is a metal grate sized such that a queen bee cannot fit through. This device is placed between the brood chamber and the honey supers stacked above. It creates a physical barrier to the queen's movement keeping her in the brood chamber, preventing her from laying eggs in the honey combs. Worker bees pass freely through the grate to carry out their honey work.

Bottom board: The standard bottom board of the Langstroth hive is comprised of a flat board encased by a perimeter wall on three sides, and one of the shorter

QUEEN EXCLUDER

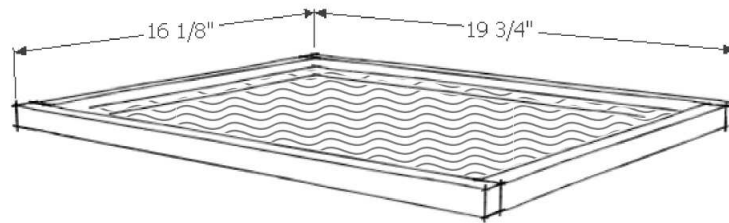


Figure 1.5: The queen excluder is placed between the brood chamber and honey super to restrict the mobility of the queen. This prevents the deposition of eggs in the honey supers.

sides is left open to serve as the hive entrance. The perimeter wall forms the base of the hive and has the same length and width as the brood chamber and honey super. Once a brood chamber is placed on top of a bottom board the inlet slot of the hive is created.

BOTTOM BOARD

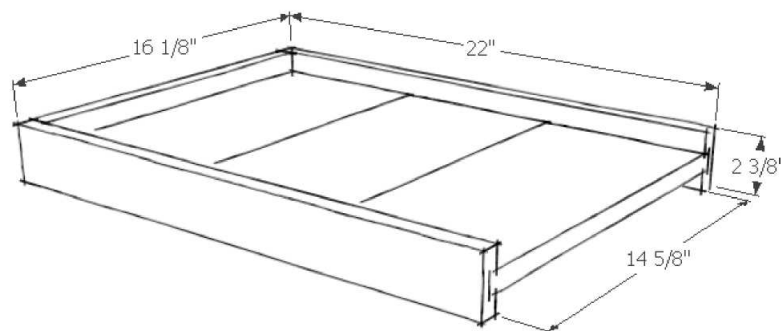


Figure 1.6: The standard flat bottom board is encased on three sides such that when the brood chamber is placed on top, the inlet space is formed along the uncovered side of the bottom board.

Top board: The top of the hive is capped with a top cover which closes off the top-most honey super. This cover is a simple board of the same length and width

as the other hive elements. Some beekeepers use modified top covers to alter the ventilation behaviour of their hive - for our study we consider a closed top cover.

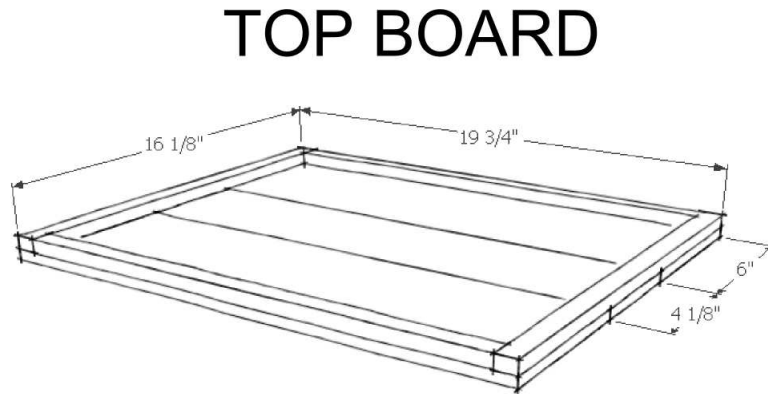


Figure 1.7: The top board covers the uppermost honey super thereby sealing off the top of the hive. Some beekeepers use modified top boards that allow ventilation, however this study only considers the completely sealed version.

The assembled hive is sealed from drafts by bees using propolis, a chewed mixture of hardened plant resins, which serves to close small gaps and stick hive parts securely together. Bees also use this sticky glue to secure the frames to the hive body. As a result a hive tool (a small, specialized pry bar) is required to pry the frames loose before removal.

1.3 Overview of Honeybee Biology

1.3.1 Honeybee Life Cycle

To facilitate the discussion of this study, a brief overview of the honeybee life cycle is in order. What makes honeybees different from other bees is their natural tendency to hoard stores of condensed nectar (in the form of honey) which they use to survive cold or dry seasons. The colony of a Western Honeybee (*Apis mellifera*, the commercial

standard) consists of roughly 20000 female worker-bees, several hundred male drones, and a single queen.

The Queen: The role of the solitary queen is to continuously lay eggs to support the hive population. Once mated, the queen is equipped with enough genetic material to lay eggs for the entirety of her two year lifespan [15], although she may mate again in life to prolong her fertility. Queens are generated from unfertilized eggs like the female workers, but are fed a special diet[56]. This food causes rapid and advanced development of the honeybee larva allowing bees to quickly produce queens when ever larvae are present in the hive.

Female Workers: Worker-bees perform all hive duties which include the maintenance of the colony environment, incubation of the brood, defense and foraging. The life span of workers is a function of time of season and ranges from 4 to 12 weeks in spring through fall[15]. Winter bees raised in the September live long to survive the duration of the winter months. Worker bees spend the first half of their life working in the hive and graduate to field duties for the remainder. Some hive duties include: thermoregulation of the brood, housekeeping, grooming, fanning, defense and construction.

Male Drones: Drones do not actively engage in many hive activities, and are primarily responsible for mating. A typical male can live up to 4 months [15]. A recent study has found that drones engage in some thermoregulatory behaviour in response to local temperature conditions[21], however their small population renders their contribution insignificant compared to that of female worker bees.

The Brood: A crucial task facing honeybees is the maintenance of their brood - a collective term which describes the en-cased larva that continuously develop inside capped-comb cells of the brood chamber. First, an empty cell is cleaned of debris by worker bees. Next, the queen lays an egg within the empty cell from

which emerges a tiny larva. The larvae are fed a mixture of substances secreted by the female nurse-bees called royal jelly[56]. As the larvae develop their diet is increasingly supplemented with pollen and honey, with the exception of queen larvae that are fed royal jelly throughout their development[56]. Eventually the cell that houses the growing larva is capped with wax and the incubation period of 10-13 days begins and during this time an incubation temperature of $33 - 36^{\circ}\text{C}$ must be maintained for healthy and timely development[56]. To ensure that the proper incubation temperature is continuously upheld, a dense blanket of worker bees (herein referred to as the bee-cluster) forms over the capped brood. The bee-cluster acts as a dynamic heating pad which can heat localized areas of the brood as required based on temperature data collected from the sensory organs of worker bees.

A typical brood chamber frame is shown in Figure 1.8 depicting the various hive contents. This frame was taken from a brood chamber early in the season, a fact which is obvious due to the relatively small size of the brood region and the presence of capped honey on the brood frame. As mentioned previously, bees typically store honey above their brood region and the capped honey cells shown in Figure 1.8 represent residual stores from winter when the hive was reduced to a single brood chamber, which will be consumed or relocated in the coming weeks.

1.3.2 Importance of Ventilation

Honeybee colonies require sufficient air exchange between the internal hive environment and the external ambient environment in order to survive. As air is exchanged across the inlet boundary, waste gases, excess heat and water vapour are expelled while fresh air is drawn inside. If ambient air temperature is low, hive ventilation occurs passively due to a driving force created by the temperature gradient between the incubating brood and the external environment. Honeybees can influence the

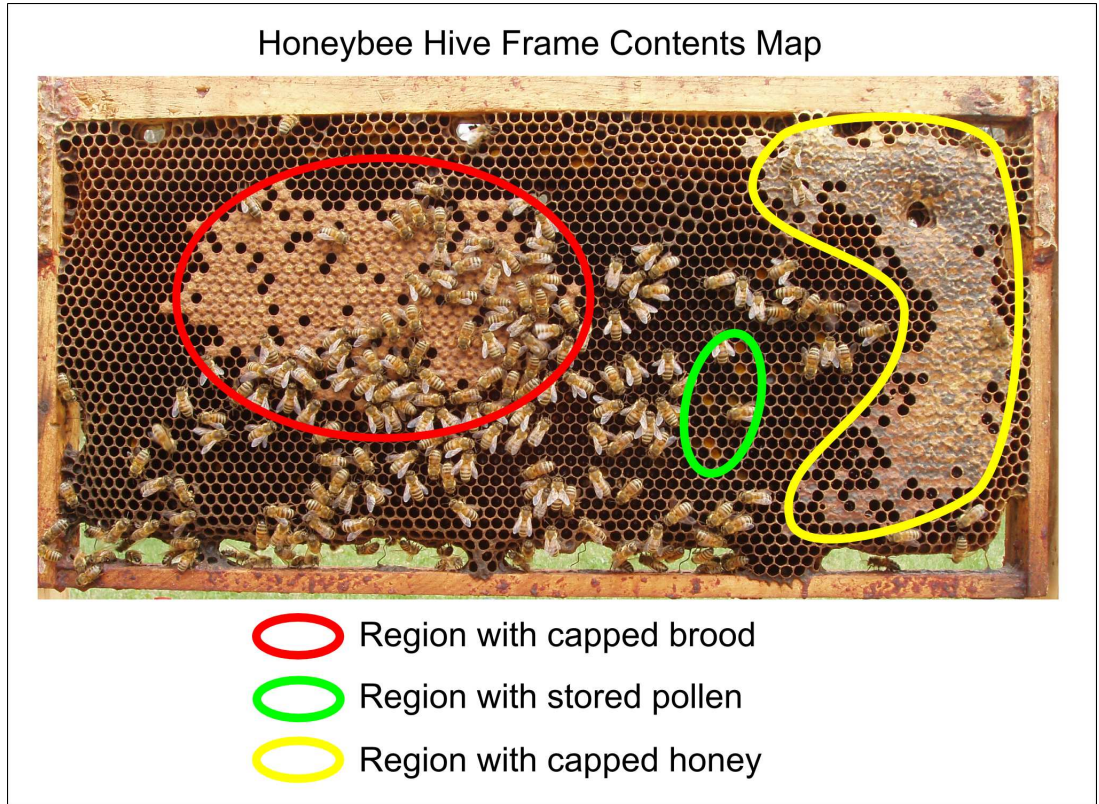


Figure 1.8: Map of comb frame contents with coloured areas denoting regions of capped brood cells, capped honey cells, and pollen stores. Note empty cells interspersed within brood region – worker bees use these cells for brood-thermoregulation activities.

rate of passive ventilation by altering the packing density of the honeybee cluster, which was demonstrated in our previous study [54] and is supported in literature investigating heat transfer in honeybee clusters [2][57]. Flow rate through the cluster increases with increasing porosity, as more air penetrates the beecover. As ambient air temperature increases and the driving force for flow (ΔT) decreases, passive air exchanges slows at which point honeybees actively engage in fanning behaviour - an energy intensive process during which many bees align themselves at the hive entrance, anchor themselves to the structure, and engage their wings to force air out of or into the hive depending on their orientation[15]. If conditions become too hot and active fanning cannot meet the ventilation demand of the colony, as a last resort

honeybees will evacuate the hive to reduce congestion (effectively maximizing hive porosity) and improve the circulation of air.

It is clear that honeybees exercise effort to maintain control over hive ventilation. As previously discussed, incubation of the brood requires tight control of temperature (within 2 °C) and ventilation becomes particularly important when temperatures become too high and cooling is required. An extreme example of active hive ventilation is referenced in a beekeeping encyclopedia, where a hive close to a burning wood pile took flame – firefighters who quenched the burning hive were surprised to find the colony intact[15]. By fanning vigorously the colony managed to protect their wax combs from melting in spite of the intense heat. Along with heat, the removal of moisture from the hive body is paramount. During the production of honey, dilute nectar collected from flowering plants condenses as the water fraction is evaporated. A large volume of water must be removed from the hive during a single season. The evaporation of moisture within the hive also plays an important part in hive cooling. Evaporative cooling occurs as influent air, warmed from passing the brood, gives up energy to vapourize water. By combining all the techniques mentioned, honeybees can remove an impressive amount of energy (in the form of heat) from their hives when required.

1.4 Investigating the Hive

1.4.1 Motivations to Study Hive Geometry

Beekeepers have continuously speculated ways to modify the traditional hive in effort improve their practice. Improvement can involve any aspect of the hives use, maintenance, and operation and, in the case of beekeeping, is often highly personalized. Although the strategies and products in use by beekeepers vary considerably in form and function, the goals of hive improvement are rather consistent. Increased honey

production is an obvious goal, and many efforts have been made to help bees speed up honey ripening by allowing more air to move through the hive. Another area of attention has been the reduction of swarming behaviour, the periodic tendency for honeybee colonies to divide and diverge, which is an undesirable outcome for beekeepers. In this event a virgin-queen leaves the colony along with a large fraction of the worker-bee population, thus seriously hampering the honey production capacity of a working hive. Studies have shown that swarming behaviour is related to the ventilation characteristics of honeybee hives, and efforts have been made to help improve air flow with the goal of reducing its occurrence. More recently research has focused on general colony health as honeybees have been receiving considerable attention in the popular media due to Colony Collapse Disorder[33].

1.4.2 Research Objective

It is reasonable to assume that changes to the standard hive geometry will facilitate changes of the fluid dynamics within the hive environment. The current investigation explores modifications to the standard hive geometry to determine how such modifications influence the physical processes within the hive environment. The geometry of a CFD model developed in a previous investigation is modified for the present work. The geometry modifications considered include various changes to the bottom board design, derived from qualitative observation of the natural nest. This study is intended to characterize changes in the flow field which result from bottom board modifications. The results will aid in the development of improved bottom board designs through quantitative comparison of various modifications and serve as a benchmark for future hive simulations.

1.4.3 Project Development

The honeybee hive simulation project began in Summer 2005 as a co-op work study. The original project sought to develop a three dimensional hive model capable of predicting flow behaviour within the hive body. This study was intended to determine whether air currents could be induced and/or exploited to disperse particles (representative of various biological control agents used to treat bee ailments) throughout the hive body. Specifically, the concept of a modified bottom board was of interest to the bee-research group responsible for the study. A student was hired from the School of Engineering at the University of Guelph (namely, the author of the present work) to develop the first hive model. The result of this preliminary attempt revealed a significant deficit of experience and knowledge relating to the theoretical aspects of CFD modeling of complex, dynamic, biological systems.

To improve the model, expertise was sought through contacts in the School of Engineering and in 2007 the project was directed to the hands of Dr. Hermann Eberl, a local expert in CFD for biological systems (Department of Mathematics and Statistics, University of Guelph). Dr. Eberl took great interest in the project and obtained funding to investigate the problem further. The project had evolved into a team effort, now including Dr. Rangarajan Sudarsan, an expert in CFD simulation with extensive experience. First, an attempt was made to develop a model of the natural honeybee nest. This proved too complicated due to the lack of quantitative data describing tree-hives. Therefore, our attention was refocused on the commercial standard and a detailed, parameterized model was developed over the next few years.

Due to the complex nature of the hive environment, care was required to construct a model that made realistic sense. The extensive work required to develop our model generated an additional research study: the characterization of the hive model, conducted 2008-2010[54]. In the present work an overview of the characterization study is presented, which highlights model details relevant to the new study and significant

conclusions that are important to consider.

1.4.4 Relevance of Study

The results of this study, compared with the results from our previous hive characterization study will provide insight to the influence of bottom board geometry on the physical processes of the hive. The response of the modified hive to changes in environmental conditions coupled with well-understood physiology of honeybees shall provide means for the optimization of an enhanced bottom board geometry. If a re-designed bottom board offers advantages to bees it will translate to advantages to beekeepers. In particular, any influence of bottom board design on the physical processes of heat and mass transfer within the hive body could prove relevant to hive health and economy.

1.4.5 Overview of Simulations

A series of CFD simulations were designed to explore the influence of bottom board geometry on the hive environment. The modification of the standard bottom board was carried out in a systematic series of experiments to ensure a careful analysis of the impacts of bottom board change. For Experiment A, a rectangular bottom cavity of variable depth was added to the existing hive to create an empty volume below the brood chamber. For Experiment B, a curved bottom cavity was added to the existing hive to create a bowl-like space below the brood chamber. For this investigation the position of the curve-apex (as described in the next section) was varied to create a series of front/back-skewed hive bottoms. As in our previous study, we limit the focus to conditions where only heating mechanisms are employed by bees. For temperatures greater than 27.5°C bees engage in active fanning along with other complicated cooling behaviours that are not considered in this study. Therefore, each case was considered for ambient air temperatures ranging from $17.5 \rightarrow 27.5^{\circ}\text{C}$.

Chapter 2

Studying Honeybees

2.1 Studying the Hive Environment

A major obstacle to building an accurate model of a working hive is the difficulty in collecting real-time measurements of hive conditions. Honeybees by nature interfere with instruments placed in their hives, coating them in wax or propylis, making it extremely difficult to obtain undisturbed measurements of hive activity. As a result, most studies into the metabolic activities of bees either focus on one single bee in a lab setting [20], or on the beehive as a whole, monitored externally [57],[11]. Thus there exists no detailed, three dimensional description of metabolic activity or any other thermoregulating activity carried out by bees within an active colony. Attempts have been made to quantify in-hive behaviours using experimental observation hives – a typical observation hive is shown in Figure 2.1. These hives mimic the honeybees’ environment allowing them to carry out regular life-functions while facilitating observation by researchers. Observation hives usually consist of a single brood and honey frame stacked within a glass window such that both sides of the frames can be seen, however these devices offer no insight into the fluid mechanics and heat transfer processes which arise in a full frame hive. In light of this fact, it is also relevant to note

that colonies in observation hives are rarely able to sustain themselves indefinitely [18], further implying the importance of proper hive ventilation to colony health.

TYPICAL OBSERVATION HIVE

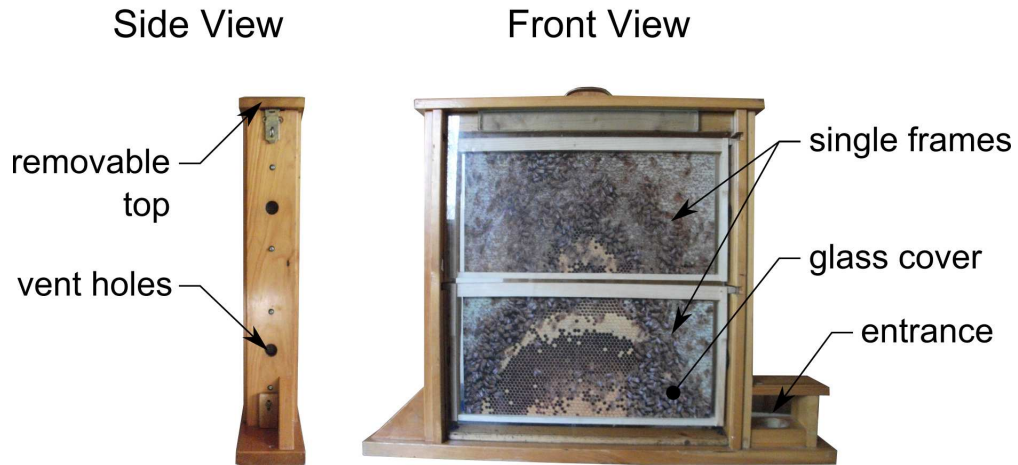


Figure 2.1: Observations hives of this type are often used to study the behaviour of bees and have a long-standing tradition in honeybee science. Two frames can be contained in this model and bees enter through a small hole at the bottom of the hive.

2.2 Honeybees and Thermoregulation

It is firmly understood that honeybees exercise a great deal of control over the temperature of their hive. Bees must maintain a brood temperature of $33 - 36^{\circ}\text{C}$ in order for their larvae to develop properly. Many studies have explored the behaviour of bees in response to various thermal situations and the mechanics of their heating and cooling activities are well documented. Worker bees produce heat by vibrating their flight muscles. Although they appear motionless, their bodies heat rapidly to temperatures exceeding 40°C [19]. Observations have revealed that some heating bees press their hot bodies against the brood caps, while others enter empty cells within the brood and pass their heat to surrounding cells [19]. The effort required by the colony for regulation of brood temperature is a function of environmental conditions.

This fact is clearly illustrated by the diurnal pattern observed for hive metabolism – bees work hard both at night to warm the brood and in early afternoon to cool it, while metabolic lows occur between these times of peak activity [22]. A recent study has shown that drones participate in heating activity as well, yet their contribution is small [21]. Working as a team, the cluster of female workers serves as a blanket of bees that insulates the brood against thermal stress. Bees pack tight to hold heat in the brood and have been shown to use their bodies to shield their brood from external heat sources[52]. When the hive becomes too hot cooling mechanisms are employed to remove excess energy from the hive. Bees gather at the inlet to engage in group fanning behaviour (as will be described in the following section) and use water to promote evaporative cooling. For the latter method, bees spread water droplets over the hot brood combs to draw off energy through evaporation [56]. For study, bees are often removed from their hive and placed into experimental situations. The data collected in these studies offer insight to the function of individual bees however do not provide an accurate picture of the functioning hive unit. Several models have been developed which investigate the heat transfer within the hive, but comprise only pieces of the whole hive picture. A model to determine the influence of empty cell heating determined that the ratio of empty cells available for heating within the brood has a significant impact on the heating economy of an individual frame [10]. A similar model was used to conduct a computer simulation of brood heating in a hypothetical frame [17], which provides the cornerstone for our simulations.

Several models for temperature in wintering clusters have been developed due to the relative simplicity and importance of the winter hive conditions. In a winter hive, the bee cluster is relatively stationary and the colony supports no brood. Experimental data was used to create an empirical model of cluster metabolism at different temperatures and a simple conduction model was used to determine the conductance of the cluster in the work of Southwick [47]. Another group developed a

model of temperature in a winter cluster considering the regulation of individual bee body temperature based on local conditions [34]. Swarm clusters occur when part of a colony leaves to establish a new nest, and behave very similarly to wintering clusters. Again, since swarm clusters are relatively stable they are much easier to study than the dynamic hive environment. Studies investigating the thermal properties of swarm clusters have shown that bees regulate the cluster core to 34°C with remarkable accuracy [31] despite full exposure to the elements.

The metabolic heat generated by honeybees has been found experimentally to depend on: (a) honeybee activity level ([50], [20]) – whether it is resting, walking or participating in active thermoregulation related activities; (b) local hive air temperature in the vicinity of the honeybee ([7]); and (c) age and sex of the honeybee ([6], [36]). In addition, the metabolic heat generation rate obtained from experiments performed on groups of honeybees (greater than 20 bees) indicate a lower value ($\frac{1}{10}$ th) than results obtained from experiments done with a single honeybee ([42]). For honeybees with moderate to high activity levels, the metabolic heat generation rate decreases linearly with temperature. In contrast, for resting or sleeping honeybees it increases with increasing temperature following a sigmoidal shape [20], with the value for resting honey bee being orders of magnitude smaller than those for the active honeybees.

Two different approaches have been used in the earlier modeling work on heat transfer and thermoregulation in honeybees: a direct and an indirect approach. In models using the direct approach, the metabolic heat generation rate obtained from experiments have been considered as a constant or as a linear or quadratic function of temperature with negative slope (valid for active honeybees) ([35], [48], [30]) or an exponential function using Q_{10} analogy (valid for resting honeybees) [34]. With the indirect method ([17]) experimentally measured values of honeybee body temperature are used along with the convective heat transfer coefficient and honeybee surface area

to evaluate metabolic heat generation rate.

2.3 Honeybees and Ventilation

Ventilation of a beehive is a topic that is not clearly represented in the literature. Again, due to the complexities that arise when studying honeybees, it is very difficult to measure hive conditions with high resolution. Consequentially, hive ventilation studies typically measure total air exchange rates and offer qualitative descriptions of group-fanning behaviour at the hive inlet, often involving modification to the inlet to facilitate measurement. A French study performed in 1964 documented the labour distribution of bees involved in cooling and foraging behaviours [26]. This work revealed that the number of fanning bees is a direct function of ambient air temperature and that bees will forgo foraging activities to take up ventilation/cooling work as temperatures increase. This result has been observed by beekeepers and is supported in the emotive work of Maurice Maeterlinck, a Nobel prize winner and hobby beekeeper. His personal experiments revealed that bees who forage in the morning hours are often observed fanning the brood in the afternoon [28]. Another study on hive ventilation revealed a tidal inflow/outflow pattern when the hive was fitted with a reduced entrance [49]. Bees fanning in unison work to evacuate a stream of stale air from the hive then, the group simultaneously stops fanning allowing for a passive influx of fresh air. In this way, the reduced-entrance-hive “breathed” at an average rate of roughly 3 breaths/min [49]. Although this experiment represents extremely idealized inlet geometry, and the author suggests that in fact, honeybees in the wild may prefer to operate larger inlets to obtain counter current flow, the results are a testament to the intricate behaviour of honeybees. Honeybees also influence hive ventilation by adjusting the packing density of the brood-cluster, a concept which was supported by our previous study [54]. By packing close together bees reduce their effective clus-

ter porosity and increase resistance to flow through it; or conversely, by spreading themselves out bees increase the effective porosity of the cluster which reduces the resistance to flow through it.

The spatial details of air-flow within the hive are speculated based on intuition and fanning activities within the nest have not been quantified. It has been discussed, based on appreciation of physics, that hot air from the bee cluster rises up into the honey super regions. If top ventilation holes are used, this warm air passes up and out of the hive, otherwise, it is forced down the sides of the hive and out through the hive inlet. As mentioned, few have undertaken comprehensive studies of hive ventilation. However, some individuals have endeavored to highlight the importance of ventilation to many vital hive process. Vladimir Shaparew discusses the importance of hive flow and the relative neglect to investigate its behaviour in the development and analysis of his Ventilating Inner Cover for Beehives [46]. In a series of non-scholarly publications, Shaparew describes his personal experiments to characterize his invention [45] [44].

Active control of hive ventilation has been linked to humidity-preference which triggers a response by fanning bees, demonstrating that honeybees exercise control over the environmental conditions within the hive [8].

2.4 Developing a full-frame hive model

The development of a full-frame hive model required the assembly of information from several studies. Data on the metabolic rates of individual honeybees in comparison with clusters of bees was used to formulate an approximate heating value. Approximate spatial data describing the location and progression of the brood was recorded in literature [15] however detailed spatial data and temporal variation was not found.

2.5 Defining the Brood

As a result of insufficient published data on brood size and position, it was necessary to implement strategies to fill the gaps. A two tiered approach was employed to collect the required data: (1) surveys were distributed to local beekeepers to collect a qualitative description of the brood and (2) field observations were conducted over the 2009 season at the University of Guelph BeeLab to collect quantifiable photographs of the brood.

2.5.1 Surveys

To develop a qualitative description of the shape, size and position of the brood in typical beehives a survey was designed to obtain data from local beekeepers. The survey requested participants to sketch the shape and position of the brood in two planes, thereby defining the brood in three dimensions. Participants were asked to complete this sketch for two different times in the season, one early in the year and one at mid season. The survey was distributed to 10 commercial apiarists with the assistance of Paul Kelly of the University of Guelph Beelab. A copy of this survey is included in Appendix A.

2.5.2 Field observations

To develop a quantitative description of the shape, size and position of the brood in typical beehives a systematic photo study was carried out from April to September of 2009 at the University of Guelph BeeLab. Visits were made to the BeeLab at one-week intervals and, with the assistance of BeeLab staff, two hives were disassembled (one at a time) and their brood chamber frames were photographed. Taking pictures was facilitated by a device used in previous brood studies, which was built and made available to our research by Paul Kelly of the BeeLab. The device featured

in Figure 2.2 supports, in fixed positions, an individual frame at one end and a digital camera at the other. The frame can be quickly photographed on both sides as the frame stand rotates on a swivel. The field study provided a quantitative basis to justify our inputs for brood shape, size and position.

It was realized shortly into the study that several uncontrolled variables were not considered, and due to this fact, the data collected are considered representative snapshots of possible hive conditions in a typical hive. The inconsistent hive components used at the BeeLab proved less than ideal: old brood chambers and honey supers did not seal effectively leading to draft influence; the hives used at the BeeLab had unique features such as extra ventilation holes and vented bottom boards; the hives contained *drone frames* – plastic frames that promote larger cell construction in order to bias site selection for drone development; old frames were used in the hives, which may have influenced the spatial development of the brood pattern. To overcome most of these uncontrolled variables, new hive components that are representative of the commercial standard must be used to conduct a similar investigation. To improve the statistical significance of the data, the brood survey should be repeated for several (at least 4) standardized hives with identical parts and maintenance procedures.

The data collected through surveys and field observations was used to define the brood position and shape within the models examined in our first study [54] as well as the present work. The data support the commonly reported description of an ‘American football’ shaped brood, if considered in three dimensions within the hive body. To define this shape mathematically, the brood is represented by an ellipse which is largest at the centre of the hive and decreases in size towards the endwalls. To define the decrease in brood size, a *brood gradient* parameter (β) was defined in our previous study, which defines the rate of reduction in terms of frame coverage.

CAMERA STAND FOR FRAME PHOTOGRAPHY

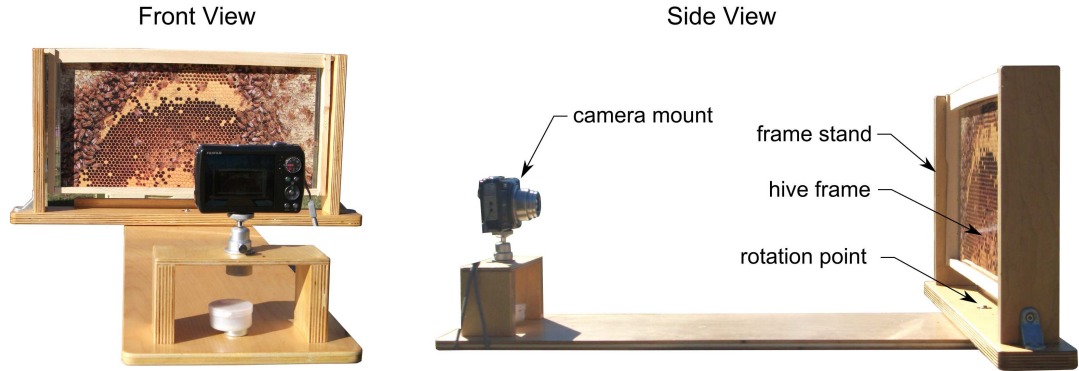


Figure 2.2: This stand was used to photograph brood frames from experimental colonies at BeeLab, University of Guelph. The stand allows both sides of a frame to be quickly captured as the frame stand can rotate upon a swivel.

2.5.3 Brood wave propagation

Visual observations of the brood frame photos revealed an interesting trend. As the season advanced, a banded pattern was observed in the brood cappings as highlighted in Figure 2.3. Logic dictates that this pattern results from the constant progression of the egg laying queen - moving to a new frame once completing a sufficient new band. This hypothesis is supported by observations described in the beekeepers encyclopedia [15]. However, work must be done to confirm the trend and to quantify the brood-front progression under controlled conditions. The banded brood pattern has not been included in any of the hive simulations to date, yet it is likely that inclusion of this feature would have an impact on flow behaviour in the hive.

2.6 CFD for Honeybees

2.6.1 The beehive computerized

Prior to our work, the use of CFD to study honeybee hives has not been documented in the literature. The complexity of the hive environment and the unavailability of

quantitative data to describe it make it difficult to create an all-encompassing model describing the hive’s physical process. In an effort to develop a model capable of testing bottom board modifications, it was necessary to build and test a model of the standard commercial hive. An intensive characterization process was conducted on our model of the standard geometry to test the validity of our representation of the hive and colony. These results combined to generate the first comprehensive CFD study of physical processes within the hive [54].

2.6.2 Defining the digital hive

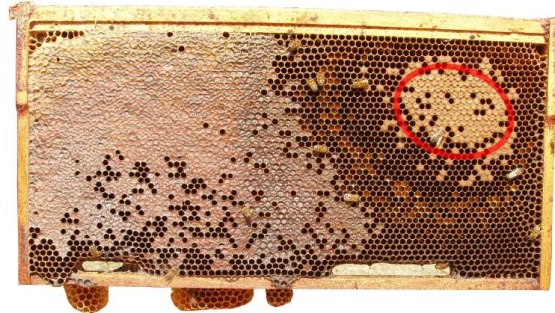
The study considered a single commercial hive composed of one brood chamber, one honey super covered with a top board, and a standard bottom board enclosing the base of the hive. Bees were added into the model by defining the region of the hive where bees cluster as a porous medium. It is assumed that bees cluster over areas where brood is present and the brood area was defined using data collected from surveys and field observations, as discussed previously.

2.6.3 Characterization

Characterization of the computer model was performed in a parametric study which focused on the influence of ambient temperature, cluster size, cluster position, and cluster porosity on physical processes within the hive. The study was limited to average summer conditions ($T_{amb} = 17.5 - 30.0\text{ }^{\circ}\text{C}$) while active fanning by bees, honey ripening and humidity transport, and the movement of bees were omitted. The results of our preliminary simulations indicated: (a) both heat and mass transfer resulting from honeybee metabolism play a vital role in determining the structure of the flow inside the beehive and mass transfer cannot be neglected; (b) the non-uniform temperature profile on the comb surfaces arising from brood thermoregulation activities enhances flow through the honeybee cluster, enhancing removal of the carbon-dioxide

produced inside the cluster effecting lower carbon-dioxide concentration next to the brood; (c) increasing ambient air temperature causes ventilation flow rate to drop, resulting in weaker flow inside the beehive.

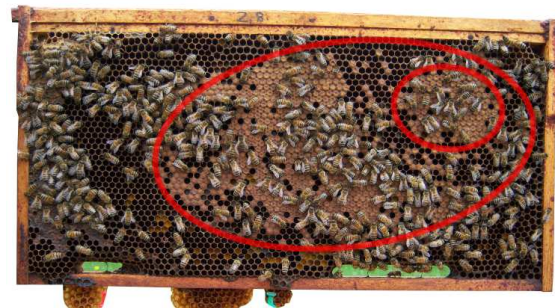
Brood Wave Propegation



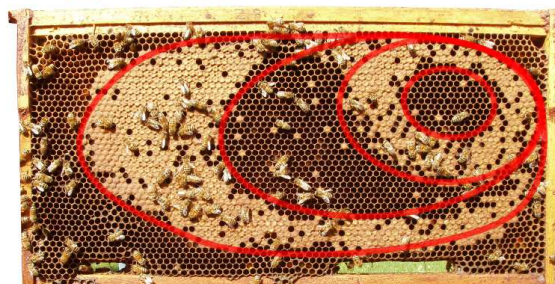
April 16 2009



April 23 2009



May 07 2009



May 14 2009

Figure 2.3: A pattern resembling wave propagation was observed upon visual inspection of the brood frame photos collected in the field study, as highlighted in the series of photos shown here.

Chapter 3

Methods

3.1 The Mathematical Model

3.1.1 The Model Domain

Internal Hive Volume

The geometry of the experimental beehives consists of the typical Langstroth hive architecture with modifications made to the bottom board. The hive volume was simplified to an 8-frame setup (10-frame is standard) to reduce the computational volume. It is assumed here, as in our previous study [54], that the flow field developed under the 8-frame simulation would be analogous to the 10-frame standard. The standard hive architecture consists of a brood chamber (the region of the hive where honeybee larva are incubated) which sits on top of a flat bottom board. Honey supers (hive compartments where honey is produced) are stacked on top of the brood chamber - the number of supers depends on the colony's productivity and ranges from 1-4. Figure 3.1 illustrates the 8-frame hive used in this study and highlights the position of the inlet slot and the porous bee cover (discussed in the next section). For our investigation, only one honey super was considered. The experimental bottom

cavities were patched onto the bottom of the hive model developed in our previous study in place of the original flat bottom board. Bottom cavity modifications were defined by the parameters α and δ which are described in Section 3.2.

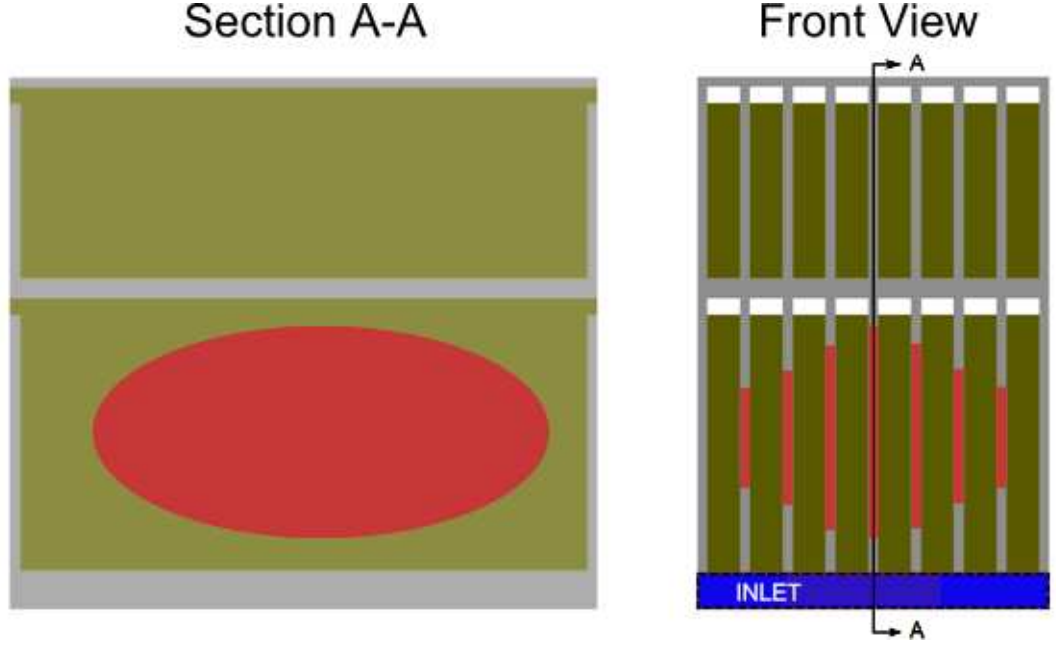


Figure 3.1: The model domain consists of an 8 frame honey super stacked atop an 8 frame brood chamber. The only opening in the hive domain is the horizontal slot along the bottom of the hive’s front face which is defined as a pressure inlet.

Porous Bee Cover

For all cases, the amount of heat generated within the hive cavity is fixed by the presence of the brood, represented by the circular shapes shown in Figure 3.1. Each simulation used the same assumed brood configuration, which was defined using information gathered from literature, surveys distributed to local beekeepers, and field research. A brief overview of the brood shape definition is now presented – for more details refer to Section 2.2 and 2.3 of our previous report[54]. The shape of the brood was defined as a rectangle with two semi circles attached to the short sides. The area of the brood shape was defined by the value of β_{bee} , given by Equation 3.1, which

represents the percentage of an individual comb surface that is taken up by brood.

$$\beta_{bee} = \frac{A_{bc}}{A_{comb}} * 100\% \quad (3.1)$$

The value of A_{bc} represents the area of the bee cover and A_{comb} is the area of the comb of interest. Considering the shape described earlier with H representing the height of the rectangle portion and W representing the width of the rectangle portion, the area of bee cover can be defined as:

$$A_{bc} = HW + \pi\left(\frac{H}{2}\right)^2 \quad (3.2)$$

The proportions of the rectangle were defined by setting the value of W on the centre beecover volume (# 4 of 7) to 0.85 times the width of the comb face. This value was chosen based on visual inspection of the brood frame photos and of active beehives in the field. All other beecover volumes were defined based on the ratio of W to H established for the centre beecover volume. The centre beecover volume was centred on the adjacent frame surfaces. It is assumed in the present work, as in our previous study, that the size of the bee cover is larger than the size of the brood area beneath it, which is defined by Equation 3.3.

$$\beta_{brood} = \frac{A_{brood}}{A_{comb}} * 100\% \quad (3.3)$$

The size difference is defined by a fixed value for $\beta_{ratio} = 0.3$, given by Equation 3.4, which represents the ratio of bee cover to brood area. Using these four relationships, the size of the brood area and the size of the bee cover over it can be defined on any comb given a value of β_{bee} .

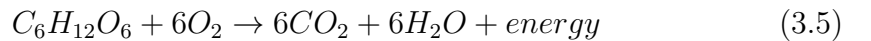
$$\beta_{ratio} = \frac{A_{brood}}{A_{bc}} \quad (3.4)$$

To mimic the 'American football' brood shape described by beekeepers and by our field observations a brood gradient was defined. By changing the value of β_{bee} at different locations in the hive, the shape of the brood, when considered in three dimensions, changes as well. To create the desired shape, a large value of β_{bee} was set on frames at the middle of the hive and small values of β_{bee} were set on frames near the walls (no brood was defined on frames facing the walls). This configuration is shown graphically in Figure 3.1.

For the present investigation one brood configuration was selected to be used in all of the modified bottom board cases. We selected a brood configuration that was representative of average conditions (relative to our previous study): brood gradient defined by $\beta_{bee} = 70 - 50\%$.

Heat and mass transfer inputs

1. Heat and mass transfer from comb surfaces: The energy expelled from the hot brood of the colony helps drive the natural convection currents that passively circulate air in the hive. In our simulation, the contribution of the brood to the hive energy balance was simplified by applying a temperature profile to the surface of combs with brood. This method replaced the need to solve the comb-side heat transfer problem as performed in [17].
2. Heat and mass transfer from honeybees: Honeybees consume sugar for energy and in the process produce heat and exhaust CO_2 and water vapour as waste. The chemical reaction described in Equation 3.5 shows that for every mol of glucose, a bee consumes 6 mol of O_2 while generating 6 mol CO_2 and 6 mol H_2O . The result is a net transfer of mass and energy to the hive air.



The transfer of energy from the bee phase of the porous medium is modeled as the convective heat loss from bees to the air within an individual cluster. In this case conduction and radiation loss to the air are neglected. The convective heat loss equation for a bee given by Equation 3.6 is not solved directly for each bee, since we have simplified the population using a porous medium formulation. Instead, the energy source is incorporated into the energy equations for the porous medium, as will be discussed in detail in Section 3.1.3.

$$G_{bee} = h_{ba}A_{bee}(T_{bee} - T_{amb}) \quad (3.6)$$

where, G_{bee} , $h_{bee \rightarrow air}$, A_{bee} , T_{amb} and T_{bee} are the metabolic heat generated by a honeybee per unit time, heat transfer coefficient for free convection/radiation from the honeybee to air, surface area of the honeybee exposed to air, temperature of the air in the vicinity of the honeybee, and the temperature of the honeybee body. Equation 3.6 implies that the heat generated by a bee per unit time is equal to the energy lost by the bee to its surroundings by convection, and neglects conductive heat loss to the comb surface and within the bee body.

3. Bee colony thermoregulation mechanisms: The range of temperature considered in the present study ($17.5 \rightarrow 27.5^\circ\text{C}$) was selected such that only heating activities need to be considered in our model. Bees engage in several methods of heating to maintain proper brood temperatures, however we do not treat these activities explicitly. As in our previous study, the heating behaviour of bees is approximated by fixing the ratio of actively heating bees verses in-active bees (designated R_{active}) in each bee cover. For the present study, this value is set to 0.6 meaning 60% of the bees in each cover are actively engaged in heating activity and these bees are radomly spread throughout the bee cover in areas where brood are present.

3.1.2 Assumptions of the Mathematical Model

The flow within the enclosed hive structure can be driven by several mechanisms including: buoyancy driven flow and natural convection, forced convection by fanning bees, and draft-ventilation from external wind. As in our previous investigation, we refined the scope of our simulations using the following assumptions:

1. Air temperature outside the hive is constant
2. All honeybees in the beehive are contained within the bee cover volumes
3. Bee thermal response mechanisms are engaged in heating only – cooling mechanisms are not considered
4. Conjugate problem is not solved - heat transfer between comb cells is neglected
5. Mass transfer has an effect on natural convection flow - density of air is a function of temperature *and* species concentration
6. Bee cover modeled as a porous medium
7. Metabolic heat generation rate modeled as a function of local bee activity and temperature
8. Metabolic heat generation rate is not a function of time
9. Comb surface temperature is not a function of time
10. Flow is steady and laminar
11. No thermal equilibrium between bee phase and air phase in porous medium
12. Effect of humidity on air flow is not considered

Detailed descriptions of each assumption and their implications for our study are presented in Section 3.2 of our previous report [54].

3.1.3 Governing equations

The flow inside the hive body, which we define as a partially porous enclosure, is modeled using a one-domain formulation where in the fluid domain is also treated

as a porous domain having a porosity $\phi = 1$. In the one domain formulation, we combine the terms for the porous and the fluid domains into one set of generalized conservation equations. In this way, the transition from porous to fluid domain is achieved by specifying the spatial variation of thermophysical properties. Gobin and Goyeau [14] verified the validity of this one domain formulation in comparison with a two domain formulation and concluded that provided sufficient care is taken in the numerical approximations, both approaches lead to similar results for the simulation of heat and fluid flow in fluid-porous domains.

The following set of equations govern the mass, momentum, heat and species transport in the porous medium with no thermal equilibrium ([32], [5], [4], [27], [29]).

Continuity Equation:

$$\nabla \cdot (\rho_f \vec{v}) = S_m \quad (3.7)$$

where: ρ_f is density of the air mixture in kg/m^3 ; $\vec{v}$ is the velocity vector in ms^{-1} ; ∇ is gradient operator in m^{-1} , and S_m is the source or sink term for mass generation in kg/m^3s which has non-zero value only inside bee cover volumes due to honeybee metabolism and the associated generation of CO_2 and water vapor.

Momentum Equation:

$$\nabla \cdot (\rho_f \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\vec{\tau}) + \rho_f \vec{g} + \vec{S} \quad (3.8)$$

where: p is the static pressure in Pa; $\vec{\tau}$ is the stress tensor in Pa; $\rho_f g$ is the gravitational body force in Nm^{-3} ; $\vec{S}$ is the external body force in Nm^{-3} in which we include all other model-dependent source terms such as resistance to flow offered by porous media. The stress tensor $\vec{\tau}$ is given by

$$\vec{\tau} = \mu \left((\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I \right) \quad (3.9)$$

where: μ is the dynamic viscosity in Pa s; T is transpose operator; I is the unit tensor; and the second term on right-hand side is the effect of volume dilation.

The source term $\vec{S}$ with Cartesian components S_j is used to capture the resistance offered to the flow by the porous medium. The source term has zero value outside the bee cover volumes. The resistance offered by the porous medium is determined by a combination of viscous surface friction and drag forces exerted by the porous medium. Different formulations are available to model the resistance, in our study the momentum source term is modeled using the Darcy–Forchheimer expression ([23]) given by:

$$S_j = - \left(\frac{\mu}{K} + C_2 \frac{1}{2} \rho_f v_{mag} v_j \right) \quad (3.10)$$

where: v_j are the Cartesian velocity components in the x,y and z directions in ms^{-1} and v_{mag} is magnitude of the velocity in ms^{-1} . The parameters K and C_2 are the permeability of the porous medium in m^2 and internal resistance in m^{-1} . They depend on the geometrical shape of the porous medium solid phase, its surface roughness, the porosity, ϕ , of the porous medium and the particle effective diameter d_p . The effective particle diameter d_p [13] is defined as

$$d_p = \left(\frac{6V_{bee}}{\pi} \right)^{\frac{1}{3}} \quad (3.11)$$

where V_{bee} is the volume of a worker honeybee. A worker honeybee is assumed to be a cylinder with length of 11 mm and diameter of 3 mm as suggested in [2].

For a honeybee that is assumed to be a smooth particle, the Ergun equation[9] is applied to get the value of the coefficients as given in the expression below

$$\frac{1}{K} = \frac{150(1 - \phi)^2 \lambda^2}{d_p^2 \phi^3} \quad (3.12)$$

$$C_2 = \frac{3.5(1 - \phi)\lambda}{d_p\phi^3} \quad (3.13)$$

where: ϕ is the porosity of the medium and λ is shape factor [13] given by

$$\lambda = \frac{A_{bs}}{\pi d_p^2} \quad (3.14)$$

where A_{bs} is the surface area of a honeybee in m^2 .

Energy equation for the fluid phase:

$$\rho_f(c_p)_f \vec{v} \cdot \nabla(T_f) = \phi \nabla \cdot (k_f \nabla T_f) + h a_{sf}(T_b - T_f) \quad (3.15)$$

where: $(c_p)_f$ is specific heat capacity of air in units $\frac{J}{kg \cdot K}$; k_f is thermal conductivity of air in $W m^{-1} K^{-1}$; T_f is air temperature in K; T_b is local bee phase temperature in K; h is heat transfer coefficient at the air-honeybee interface and a_{sf} is specific surface area of the honeybee phase in the porous medium(surface area per unit volume of the honeybee).

Energy equation for the honeybee phase:

$$(1 - \phi) \nabla \cdot (k_{bf} \nabla T_b) - h a_{sf}(T_b - T_f) + (1 - \phi) q_{bp}'' = 0 \quad (3.16)$$

where k_{bf} is thermal conductivity of the honeybee, T_b is local honeybee phase temperature in K; and q_{bp}'' is the metabolic heat generation rate by the honeybee per unit volume of the honeybee in W/m^3 . The last term in the energy equations for the fluid and solid/bee phase which appears with opposite signs in both these equations represents the heat transfer between the honeybee phase and air in its vicinity.

In this study, we assume that the conduction inside the honeybee phase represented by the first term in (3.16) is negligible compared to the other two terms. With this assumption, if we drop the conduction term we can collapse the bee-phase energy

equation into the fluid-phase energy equation and rewrite the fluid-phase equation as given below:

$$\rho_f(c_p)_f \vec{v} \cdot \nabla(T_f) = \phi \nabla \cdot (k_f \nabla T_f) + (1 - \phi)q''_{bp} \quad (3.17)$$

Species Transport Equation:

$$\nabla \cdot (\rho_f \vec{v} Y_i) = - \nabla \cdot (J_i) + S_i \quad (3.18)$$

where: ρ_f is density of fluid in kg/m^3 ; Y_i is mass fraction of species i in air mixture; $\vec{v}$ is velocity vector in m/s ; J_i is diffusion flux of species i in $\text{kgm}^{-2}\text{s}^{-1}$ given by

$$J_i = -\rho_f D_{i,f} \frac{\partial Y_i}{\partial x_i} \quad (3.19)$$

where $D_{i,f}$ is diffusion coefficient of the species i in the mixture f; S_i is source or sink term in $\text{kgm}^{-3}\text{s}^{-1}$ due to bee metabolism, which has a non zero value only inside the bee cover volumes; and ∇ is the gradient operator in m^{-1} . A constant value is used for the diffusion coefficients of the different species, and the this value is applied inside the porous bee cover and in the fluid space in the fluid.

Equation of State for air:

The air is assumed to be an incompressible ideal gas mixture made up of different constituents namely carbon-dioxide, water vapor, oxygen and nitrogen. The density of the this mixture [1] is calculated as given below:

$$\rho_f = \frac{P_{op}}{R T_f \left(\frac{Y_{CO_2}}{M_{CO_2}} + \frac{Y_{O_2}}{M_{O_2}} + \frac{Y_{H_2O}}{M_{H_2O}} + \frac{Y_{N_2}}{M_{N_2}} \right)} \quad (3.20)$$

where: P_{op} is operating pressure in Pa; R is universal gas constant in $\text{J}/\text{kg mol K}$; T_f is temperature in K; Y_{CO_2} , Y_{O_2} , Y_{H_2O} , Y_{N_2} and M_{CO_2} , M_{O_2} , M_{H_2O} , M_{N_2} are the mass fraction and molecular weight (in $\frac{\text{Kg}}{\text{Kg}\cdot\text{mol}}$) of the different constituents namely

carbon-dioxide, oxygen, water vapor and nitrogen that make up the air mixture.

3.1.4 Boundary conditions

Hive boundaries

For solving the set of governing equations listed in the earlier section, the boundary conditions described below were used. For the momentum equation, along the inside walls of the beehive as well as on all the surfaces of the frames in both the brood chamber and honey super, no slip boundary conditions ($\vec{v} = 0$) were applied. On the inlet to the beehive present at the bottom of the brood chamber, a pressure inlet boundary condition was applied. This boundary condition is used as the ambient atmospheric pressure outside the beehive is known but the flow rate and/or velocity are not known and it also allows the flow to exit through sections of the inlet where the pressure exceeds the user specified inlet total pressure. The treatment of pressure inlet boundary conditions by Fluent[®] can be described as a loss-free transition from stagnation conditions to the inlet conditions. For incompressible flows, this is accomplished in Fluent[®] by application of the Bernoulli equation at the inlet boundary as explained in Fluent user manual [1].

Species transport

For the species transport equation, we apply zero flux boundary conditions on all the interior surfaces of the beehive (excluding the inlet) and on all the surfaces on the frames including the brood surfaces underneath the bee cover volumes. This boundary condition on the brood surface is a valid approximation as the metabolic heat generated by the pupae inside the brood and thereby the mass flux of the different species accompanying the brood metabolism is negligible ([17],[36],[39]) in comparison to metabolic heat generated by the honey bees in the bee cover. Along the pressure inlet boundary, whenever the flow enters the beehive from the external environment,

the value of species concentration is set to the concentration of the species assumed in the ambient air. For the simulations done in this study, the ambient air is assumed to be made up only of oxygen and nitrogen with the mass fraction of oxygen Y_{O_2} set to 0.22 and mass fraction of nitrogen Y_{N_2} set to 0.78.

Brood temperature profile

For the energy equation, all the surfaces on the inside of the beehive enclosure and on the frames except the brood surfaces underneath the bee cover regions are assumed to be insulated. For reasons explained earlier under modeling assumptions, a Dirichlet boundary condition for temperature is applied on the comb surface underneath the bee cover where the brood resides. To mimic the effect of brood thermoregulation by the worker honeybees a spatially varying temperature profile, derived from our previous study [54], was applied on the brood surface. The spatially non-uniform temperature profile is a realistic one to expect, arising as a result of the combined efforts of the thermoregulating worker honeybees. Due to reasons discussed earlier under model assumptions, in this study we neglect the time variation of the brood temperature, but mimic its spatial variation by constructing a non-uniform temperature profile on comb surfaces underneath each of the bee cover volumes. Based on the work of Humphrey and Dykes [17] the temperature is assumed to vary linearly in the direction normal to the ellipse-shape from 38 °C (set at the core of the brood surface) to 33 °C (set at the periphery of the brood region). For a detailed definition of the temperature gradient applied to the brood surface its evolution, consult Section 3.4 of our previous study [54].

Initial Conditions

Fluent uses an semi-implicit iterative method to solve the governing equations, at the start of the iterative process, the initial value of the velocity for all cells is set to zero,

the initial temperature set to 300 °K (approx. 27 °C), and the initial concentration of the different species is set to be same as their value in the ambient air.

3.1.5 Model parameters

Porosity of bee cover volume:

Porosity in a fluid saturated porous medium is defined as the fraction of its total volume occupied by the fluid, which in our case is air. If the distribution of honeybees inside each bee cover volume which is modeled as a porous medium is assumed to be uniform, the porosity ϕ of each bee cover volume can be calculated by

$$\phi = \frac{V_{air}}{V_{bc}} = 1 - \frac{V_{bee-phase}}{V_{bc}} \quad (3.21)$$

where V_{bc} is the total volume of the bee cover volume and $V_{bee-phase}$ is the total volume occupied by all honeybees present in each bee cover volume. If we assume all the honeybees have the same size and shape, the above equation can be rewritten as

$$\phi = 1 - \frac{N_{bc}V_{bee}}{V_{bc}} \quad (3.22)$$

where V_{bee} is the volume of a single honeybee, and N_{bc} is the number of honeybees present in a bee cover volume.

An estimate of the number of honeybees present in each bee cover along with volume of each bee cover is needed to evaluate porosity using (3.22). An approximate value to use for bee cover volume can be obtained from the shape of the bee cover volume seen during visual inspections, but an estimate of number of honeybees inside a bee cover volume or in the whole beehive is difficult to obtain via visual means. Earlier models studying heat transfer in winter clusters and honeybee swarms ([35],[34],[55],[25]) used either density of the honeybees (mass of honeybee per unit volume of the cluster) or number of honeybees per unit volume of the cluster as vari-

able instead of porosity. This was motivated by the fact that the earlier models were primarily conduction only models neglecting the flow through the cluster. Basak et al.[2] studying heat transfer in honeybee swarms used an estimate of number of honeybees in a swarm given by Heinrich et al [16] to evaluate the porosity. Watmough and Camazine[57] in their model on thermoregulation in honeybee clusters evaluated the density of the honeybees using the estimate of 2 bees per cm^3 at higher ambient temperatures increasing to maximum of 8 bees per cm^3 at low temperature provided by Heinrich et al [16].

In our model, we use (3.22) to compute the porosity by substituting for V_{bee} the value computed by assuming the honeybee to be a cylinder with length = $11mm$ and diameter = $3mm$ as suggested in [2] and for $\frac{N_{bc}}{V_{bc}}$ (number of honeybees per unit volume of bee cover volume) the range of values given by Heinrich et al.[16]. The range of value for porosities that resulted from this substitution was $0.4 \leq \phi \leq 0.5$. In our previous study, we investigated the influence of porosity variation on the physical processes within the hive. For the case of the present work, we fix the porosity of the beecover volumes to an average value $\phi = 0.45$. The value of porosity for each simulation is assumed to be same in all the bee cover volumes.

Metabolic heat generation rate per unit volume of honeybee

The metabolic heat generation rate per unit mass of the honeybee (g_{bee} in Watts/Kg) or per honeybee (G_{bee} in Watts) are conventionally measured using calorimetry experiments, as highlighted in Section 2.2. The metabolic heat generation rate per unit volume of the honeybee phase, q_{bp}'' , needed in (3.17) can be calculated from G_{bee} or g_{bee} after conversion as shown in the equations given below

$$q_{bp}'' = \frac{G_{bee}}{\pi(D_{bee}/2)^2 L_{bee}} = \frac{g_{bee}}{M_{bee} \pi(D_{bee}/2)^2 L_{bee}} \quad (3.23)$$

where L_{bee} and D_{bee} are the length and diameter of a honeybee modeled as a cylinder

[2] and M_{bee} is the mass of a honeybee which varies from around 80 *mg* to 110 *mg* depending on the amount of honey it is carrying. In writing the above equations, we have assumed that the heat generation is distributed uniformly throughout the volume of the bee.

Metabolic heat generation rate is measured in controlled experiments through use of direct calorimetry ([40], [37], [38]) or indirect calorimetry([6], [51], [36], [20]). In direct calorimetry experiments, the temperature increase of the air at a given flow rate flowing over a honeybee or a cluster of honeybees held inside a controlled temperature environment is measured. From these experiments, the heat generation rate per unit weight of the honeybee (g_{bee}) is calculated, from which q''_{bp} needed in our study can be calculated using (3.23). For indirect calorimetry, the change in concentration of carbon-dioxide or oxygen in air flowing at a given flow rate over a cluster of honeybees held inside a controlled chamber is measured. These experiments report either the volume rate of oxygen consumption ($\dot{V}_{O_2}$) or volume rate of carbon-dioxide production ($\dot{V}_{CO_2}$) both expressed in $\mu\text{l}/\text{min}$ per honeybee measured at STP (Standard Temperature Pressure: $T=273\text{ K}$, $P=1\text{ ATM}$) conditions. q''_{bp} needed in our governing equations can be inferred indirectly from the reported $\dot{V}_{O_2}$ or $\dot{V}_{CO_2}$, after converting the reported data to G_{bee} with the assumption that the combustion of honey is an aerobic process following the stoichiometric equation given in Equation 3.5. The steps involved in the conversion process are as outlined below:

Steps to convert $\dot{V}_{O_2}$ data to G_{bee}

1. Step #1 : Convert $\dot{V}_{O_2}$ to number of moles of O_2 consumed per unit time ($\dot{N}_{O_2}$) given that 1 mole of any gas occupies 22.4 Liters at STP.
2. Step #2: Convert $\dot{N}_{O_2}$ to number of moles of glucose consumed per unit time $\dot{N}_{C_6H_{12}O_6}$ from stoichiometric equation given in Eq.3.5, i.e., 1 mole of glucose needs 6 moles of oxygen.

3. Step #3: Convert $\dot{N}_{C_6H_{12}O_6}$ to G_{bee} using the fact that 1 mole (180 g) of glucose ($C_6H_{12}O_6$) produces 2874 kJ of energy.

In the model used in this study, the value for metabolic heat generation rate at the centroid of each grid cell inside the bee cover volume is assumed to be a function of local air temperature and activity level of the honeybee at that location. The activity level of the honeybees involved in brood maintenance is specified by setting the value of R_{active} , the ratio of number of active honeybees to total number of honey bees at each location inside the bee cover volumes. In our work, we make the following assumptions while setting the value of R_{active} : (a) the honeybees inside the beehive can be assigned to one of the two activity levels namely active or passive, which can be logically extended to include more activity levels in the future; (b) the number of active honeybees in each bee cover is proportional to the size of the brood underneath it; and (c) R_{active} is assumed to be constant inside each bee cover volume due to the lack of sufficient data to fix activity distribution of honeybees inside the hive. As we move from one bee cover to the next one along the span of the hive, the number honeybees and thus, the number of active-heating bees, reduce by same proportion as the bee cover volume keeping their ratio constant.

The value of q''_{bp} at each location inside the bee cover volume is given by

$$q''_{bp} = \beta_{corr}((1 - R_{active})g_{passive}^v(T) + R_{active}g_{active}^v(T)) \quad (3.24)$$

where $\vec{r}$ is the position vector, $g_{active}^v(T)$ and $g_{passive}^v(T)$ are the metabolic heat generation rate per unit volume of an active and passive honeybee at the temperature T and $\beta_{corr} = 0.10$ a correction factor used to scale values obtained from experimental measurements done on single honeybees into appropriate values for groups of honeybees. A similar correction factor β_{corr} was used in the modeling work on honeybee swarms in [2].

The earlier models studying heat transfer in honeybee clusters during the winter used different expressions to quantify the temperature dependence of metabolic heat generation rate valid in the temperature range ($-10 \rightarrow 15^\circ\text{C}$) prevalent during the winter. The expressions used did not explicitly account for the different activity levels of the honeybees which would be present during the summer and cannot be extended to the range of temperature prevalent inside the beehive during the summer. In our study, the expression used for $g_{active}^v(T)$ and $g_{passive}^v(T)$ was obtained from the indirect calorimetry experimental data of Stabentheiner et al.[51]. They measured the oxygen consumption rate of honey bees ($\dot{V}_{O_2}$) in $\mu\text{L min}^{-1}$ per honeybee as a function of temperature performing different activities which were labeled in their study as A, B,C, and D where A corresponded to small or no movements, B to low activity, C to medium activity, and D to fast activity as well as for a resting honeybee. The medium activity level C from [51] was chosen to represent the active honeybee in our model,while the activity level B was chosen to represent the less active honeybee. For both these activity levels, the $\dot{V}_{O_2}$ data in [51] showed a decrease with increasing temperature. A linear function was assumed to describe the temperature dependence given by

$$\dot{V}_{O_2}^{active} = A_{active} + B_{active}T \quad (3.25)$$

$$\dot{V}_{O_2}^{passive} = A_{passive} + B_{passive}T \quad (3.26)$$

where the coefficients A_{active} , $A_{passive}$, B_{active} , and $B_{passive}$ were obtained by least square fit (correlation coefficient $r^2=0.92$) to the data extracted from [51]. Using the steps outlined earlier, the oxygen consumption rate expressed by the (3.25) was converted to get the the source terms occurring in the energy and species transport equations of the present simulations.

Source terms: Species Transport and Continuity Equations

The source term S_i (units: Kg/m^3sec) that appears in the species transport equations (3.18) where i stands for either of CO_2 , H_2O , O_2 or N_2 and the source term in the continuity equation S_m (3.7) are both related to the source term q''_{bp} that appears in the energy equation (3.15). This relationship is to be expected as the same honeybee combustion process that generates the heat is accompanied by consumption of oxygen and production of water vapor and carbon-dioxide, i.e., combustion of 1 mole (180 g) of glucose ($C_6H_{12}O_6$) produces 2874 kJ of energy in addition to producing 6 moles of water vapor and carbon-dioxide and consuming 6 moles of oxygen. Therefore a conversion factor can be worked out to compute the S_i terms once q''_{bp} has been obtained as a function of local temperature as explained in Section 3.1.5. To speed up the calculation, this conversion is done outside the Fluent[®] UDF where we calculate the coefficients A_i and B_i which are the coefficients appearing in a linear function written for $S_i(T)$ i.e., $S_i = A_i + B_i T$, where T is the temperature of the air in centigrade.

The source term S_m in the continuity Equation (3.7) is given by

$$S_m = S_{co_2} + S_{h_2o} - S_{o_2} \quad (3.27)$$

and it has a positive value inside each of the bee cover volumes, i.e, net mass is added to the air due to combustion of honey.

3.1.6 Post-processed quantities

In this study, to understand the influence of different model parameters, we computed integral values of quantities over different regions inside the beehive. These quantities, used in conjunction with conventional flow visualization techniques like contour and vector plots, provided us an efficient way to understand the subtle change in flow

behaviour that arises due to changes in hive geometry. The definition of the different integral quantities and the methods used to calculate them are listed below:

1. **Ventilation flow rate:** Ventilation flow rate (expressed in Liters/min) is the measure of the air exchange between the beehive and the external environment. It can be quantified by specifying either the inflow rate or the outflow rate, where the inflow and outflow rate are defined as the volume of air entering and leaving the beehive per minute. In a conventional Langstroth beehive like the one in our study where we have no additional openings, the air has to both enter and leave the beehive through the inlet in the bottom of the brood chamber. In such a case, the volume inflow and outflow rate are given by

$$\dot{V}_{inflow} = \int_{\Omega_i} |\vec{v} \cdot \vec{n}| dA; \quad \dot{V}_{outflow} = \int_{\Omega_o} |\vec{v} \cdot \vec{n}| dA \quad (3.28)$$

where $\vec{v}$ is the fluid velocity vector, $\vec{n}$ is the outward pointing normal to the inlet face and Ω_i and Ω_o are the area of of inlet face over which the flow enters and exits the beehive respectively, i.e., $\vec{v} \cdot \vec{n} < 0$ over Ω_i and $\vec{v} \cdot \vec{n} > 0$ over Ω_o . Inside each of the bee cover volumes, honeybee metabolism (3.5) results in addition of carbon-dioxide and water vapor along with removal of oxygen from the air mixture. This is captured by setting nonzero values to the source terms, S_{CO_2} , S_{O_2} and S_{H_2O} in the righthand side of (3.18). The net effect for the air mixture as a whole is a positive value for S_m , the mass source term in (3.7) inside each bee cover volume where $S_m = S_{CO_2} - S_{O_2} + S_{H_2O}$. With $S_m > 0$ inside each bee cover volume, the application of mass balance to the whole beehive results in the mass flux of air into the beehive being less than the mass flux out of the beehive. This difference when translated into flow rates is further enhanced by the difference in density between the ambient air entering the beehive and the stale air exiting it. This ensures that $\dot{V}_{inflow}$ is always less than

$\dot{V}_{outflow}$. However, since S_m is relatively small, the difference in absolute value between $\dot{V}_{inflow}$ and $\dot{V}_{outflow}$ is not considerable. For example, for a simulation with β gradient =70-30, ϕ =0.45, T_{brood} = non-uniform at $T_{amb} = 20^\circ\text{C}$, we calculated a $\dot{V}_{inflow}$ of 3.10441 L/min while $\dot{V}_{outflow}$ was 3.17948 L/min. In our discussion and in the presentation of our results, we report only the $\dot{V}_{inflow}$ with the understanding that the corresponding $\dot{V}_{outflow}$ would be slightly larger.

2. **Heat transfer related quantities:** The honeybees inside each bee cover volume generate heat, some of which is transferred to the brood while the rest of it is lost to the air via convection and diffusion. The total heat generated per second Q_{bc}^i by the honey bees occupying each bee cover volume is given by

$$Q_{bc}^i = \oint_{\Omega_i} (1 - \phi) q_{bp}'' dv, \quad i = 1 \text{ to } 7 \quad (3.29)$$

where Ω_i is the volume of *beecover_i* and q_{bp}'' is the rate of heat generation per unit volume at each location inside the bee cover volume.

The net heat transferred per second to the comb surfaces(cs) underneath each bee cover volume is given by

$$Q_{cs}^i = \int_{cs} q_{cs}'' dA, \quad i = 1 \text{ to } 7 \quad (3.30)$$

where q_{cs}'' is the heat flux on the comb surface and integration for each i is done over both the comb surfaces that make up each bee cover volume.

The net heat flux to the air outside Q_{net}^i from each bee cover volume is given by

$$Q_{net}^i = Q_{bc}^i - Q_{cs}^i, \quad i = 1 \text{ to } 7 \quad (3.31)$$

In addition to the listed heat transfer quantities, we also computed the average body force in each of the bee cover volumes given

$$BF_{avg}^i = \frac{\oint_{\Omega_i} |(\rho - \rho_{ref})g| dv}{V_{\Omega_i}} \quad (3.32)$$

where V_{Ω_i} is the volume of the bee cover volume and the reference density ρ_{ref} is the density of the ambient air outside the beehive evaluated using (3.20) substituting $T = T_{amb}$ and $Y_{O_2} = 0.22, Y_{N_2} = 0.78$ and $Y_{H_2O} = Y_{CO_2} = 0$ respectively.

3. **Mass transfer related quantities:** Honeybee metabolism produces an equal number of moles of carbon-dioxide and water vapor for each mole of honey consumed as seen in Equation(3.5). With the diffusivities of both carbon-dioxide and water vapor being around the same order of magnitude, the integral quantities computed using concentration of each inside the bee cover volumes will follow the same trend. In view of this, we present only carbon-dioxide related quantities in each bee cover volume in the result section. The total mass $M_{CO_2}^i$ and the mass generated per second $\dot{M}_{CO_2}^i$ of carbon-dioxide inside each bee cover volume is given by

$$M_{CO_2}^i = \oint_{\Omega_i} \rho Y_{CO_2} dv; \quad \dot{M}_{CO_2}^i = \oint_{\Omega_i} S_{CO_2} dv \quad (3.33)$$

where Y_{CO_2} is the mass fraction of carbon-dioxide and S_{CO_2} is the rate of carbon-dioxide generation per unit volume of the bee cover. The ratio of $M_{CO_2}^i$ and $\dot{M}_{CO_2}^i$ which has the units of time (seconds) is referred to in this study as pseudo residence time (τ_i). It is used as a measure of the convective flux through the bee-cover volume with the larger value of τ_i indicative of a slower flow through the bee-cover and vice-versa. In addition, we also quantified the ability of the

flow exiting the beehive to remove some of the carbon-dioxide produced inside the beehive, by calculating the carbon-dioxide clearance efficiency, η expressed as a percentage given by

$$\eta = 100. \times \frac{M_{out}^{co2}}{\sum_i \dot{M}_{co2}^i} \quad (3.34)$$

where the numerator is the mass flux of carbon-dioxide out of the beehive and the denominator is the sum of mass of carbon-dioxide generated per second inside each of bee cover volume present in the beehive.

3.2 Simulations Conducted

3.2.1 Experiment A Addition of a Rectangular Bottom Cavity of Variable Depth (δ)

For Experiment A the standard hive was modified by removing the original flat bottom board and adding a rectangular cavity below the brood chamber. The rectangular bottom cavity is an extension of the original bottom board to variable depths $\delta = \{0, 10, 30, 50, 70, \text{ and } 90 \text{ mm}\}$ in the negative Z-direction as illustrated in Figure 3.2. For each depth the flow field was calculated for a series of cases defined by variation of the parameter $T_{amb} = \{17.5, 20.0, 22.5, 25.0, \text{ and } 27.5^\circ\text{C}\}$, which represents the external air temperature.

The model domains for the rectangular bottom cases were fit with a hexagonal grid made up of 3199872 elements. A very fine mesh was required to capture the boundary layer effects generated by the narrow bee-space gap. Due to the extreme size of the grid High Powered Computing clusters provided through SHARCNET were required to solve the problem.

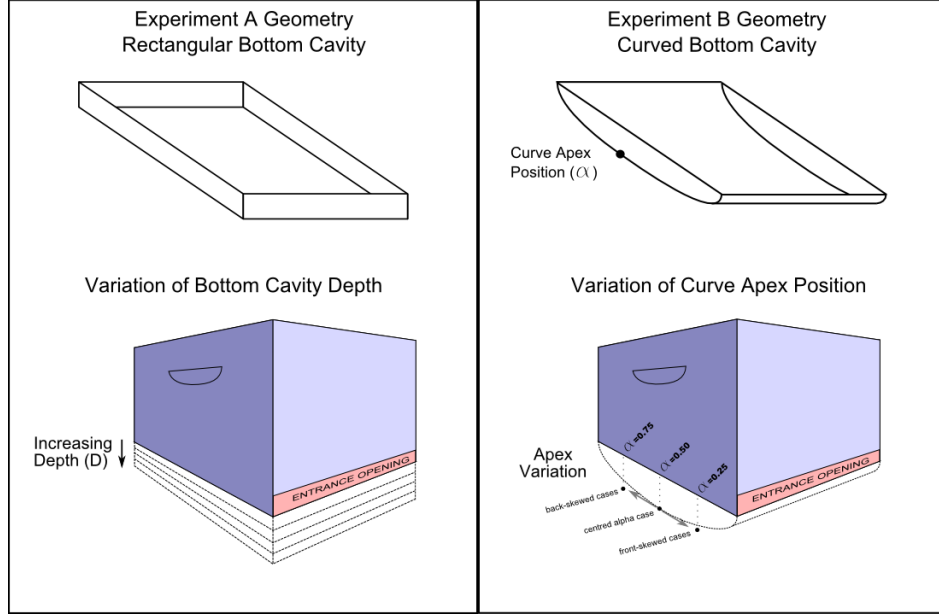


Figure 3.2: (LEFT PANE) the bottom board modification explored in Experiment A is an extension of the original rectangular shaped board in the downward direction to variable depths δ , (RIGHT PANE) the bottom board modification explored in Experiment B is a curved bottom board that reaches a maximum depth of 70 mm at an apex point α , the position of which is variable

3.2.2 Experiment B Addition of a Curved Bottom Cavity of Variable Apex Position (α)

The addition of cavity curvature consisted of patching a half-ellipse shape to the bottom of the hive box along the YZ-plane as shown in Figure 3.2. The curve-apex position, a variable parameter represented by α , was considered for 11 configurations defined by $\alpha = \{0.10, 0.25, 0.30, 0.40, 0.45, 0.50, 0.55, 0.6, 0.70, 0.75, \text{ and } 0.90\}$ where 0.50 represents an apex centred on the YZ-plane. Two series were considered at varying apex depths $\delta = \{50, 70 \text{ mm}\}$ to allow comparison with Experiment A results. Another set of simulations were carried out to test the effect of variable external temperature $T_{air} = \{17.5, 20.0, 22.5, 25, \text{ and } 27.5^\circ\text{C}\}$.

The model domain was meshed using hexagonal grid elements which amounted to 3103616 cells. A very fine mesh was required to capture the boundary layer effects

generated by the narrow bee-space gap. The curvature of the bottom cavity induced some cell distortion; however a grid-scheme was developed to minimize this effect.

Using the default values for under-relaxation factors set by Fluent convergence of the solution was usually achieved within 8000-12000 iterations. Wall-clock time for each simulation case was approximately 48-72 hours. All simulations were performed on the High Powered Computing (HPC) network of SHARCNET and as such, various computing platforms were used depending on availability.

3.2.3 Mathematical Solver: ANSYS Fluent

The model solution was calculated using a commercial CFD code Fluent, which is an all-purpose solver for fluid dynamics problems. Fluent uses a finite-volume method to resolve the governing equations, which describe the physical processes occurring within the experimental domain, into algebraic equations that can be solved numerically. This method generates a system of linear algebraic equations which are solved iteratively to obtain a result. Convergence of the solution is monitored by observing the scaled-residual quantities of each model equation - for our investigation convergence was obtained once residuals for continuity, species transport, and velocity variables were below 10^{-5} and the residual for the energy equation was below 10^{-6} . In addition to monitoring the residuals, the volume-averaged molar concentration of CO₂ in each bee-cluster region and the net heat flux from each of the comb surfaces underneath each bee-cluster were monitored. If the residuals met their set convergence criteria and the two monitored quantities converged towards a constant value, it was considered that the simulation had reached a steady solution.

Chapter 4

Results and Discussion

4.1 Experiment A

ADDITION OF A RECTANGULAR BOTTOM CAVITY OF VARIABLE DEPTH

4.1.1 Experiment A Results

The air flow characteristics within the hive changed significantly when a bottom cavity was added to the hive. The parameter δ defines the bottom cavity depth and the case of $\delta = 0$ mm represents the standard flat bottom board found in the traditional hive geometry. For this case, the air entering the hive flows to the back and is forced up. A fraction of the flow stream penetrates the upper hive compartment while the remainder, once meeting the warm hive air, is redirected and forced back out through the inlet. Adding a bottom cavity to the hive allows the cooler air entering the hive to settle quickly into the bottom. The flow then travels along to the back of the hive where it is forced up to meet the warm hive air and most of the flow is pushed back out the front of the hive. Figure 4.1 shows the evolution of the flow field with increasing bottom cavity depth. The most significant feature of the flow field is the vortex which develops at the front of the hive, which becomes clearly defined once

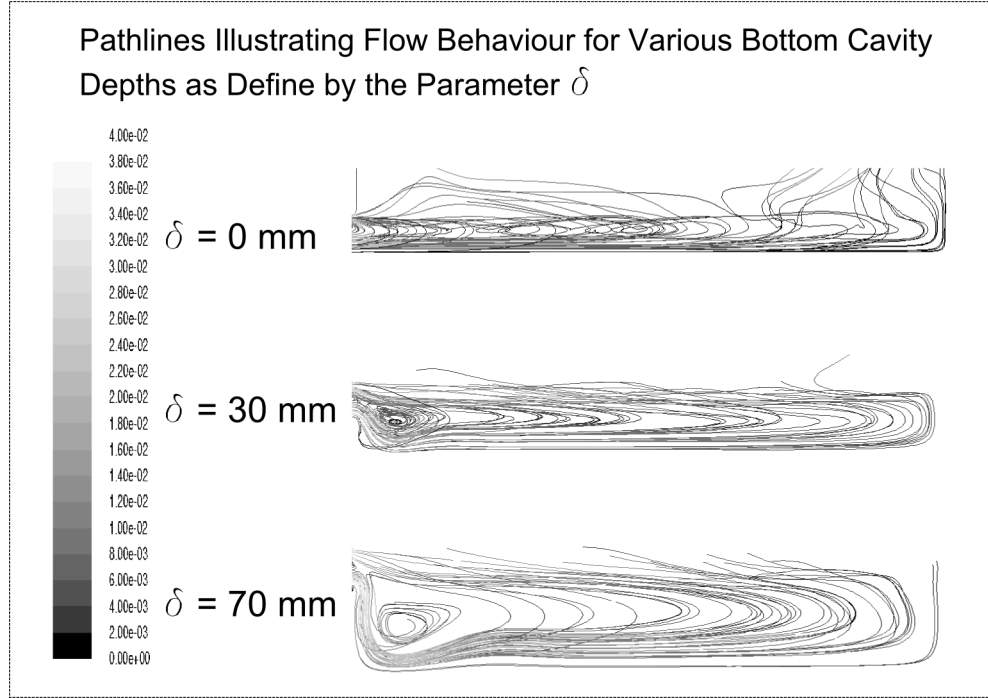


Figure 4.1: A plot of flow pathlines in the bottom cavity section of the hive for various cavity depths (defined by the parameter δ) illustrates the differences in flow behaviour that arise due to geometry change.

$\delta = 70$ mm.

In all cases, the driving force for air flow is the temperature gradient (ΔT) created between the warm brood (maintained at $33 \rightarrow 35^\circ\text{C}$) and the outside ambient temperature T_{amb} . For cases where the temperature gradient was relatively large ($T_{amb} < 25^\circ\text{C}$) increasing the depth of the bottom cavity resulted in a significant increase of the ventilation flow-rate. As illustrated in Figure 4.2, the increase in ventilation flow rate follows an exponential trend that reaches a maximum once the bottom cavity is extended to a depth of $\delta = 70$ mm.

The largest increase in ventilation flow-rate was observed for the cases with the lowest ambient air temperature ($T_{amb} = 17.5^\circ\text{C}$), which correspond to cases having the largest temperature gradient and the largest driving force. As the bottom cavity depth was increased from $\delta = 0 \rightarrow 90$ mm the ventilation flow rate across the hive

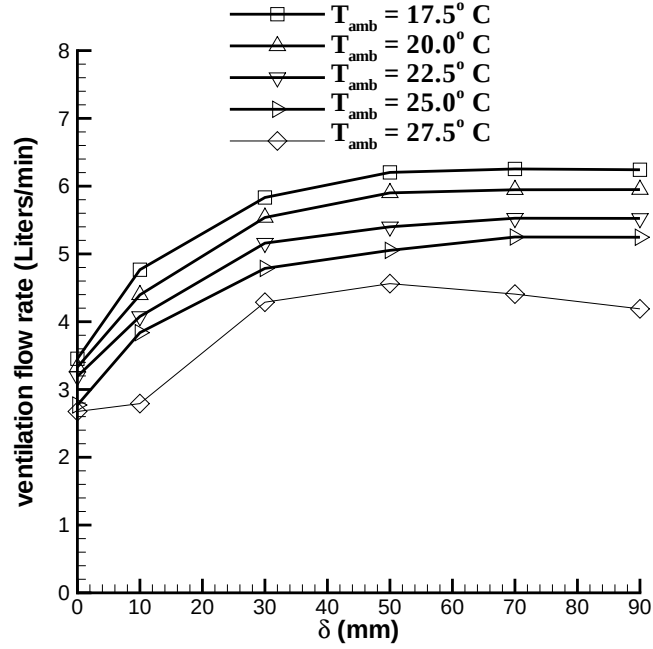


Figure 4.2: Plot of ventilation flow rate (L/min) across the hive inlet for various values of δ under different ambient temperature conditions.

inlet increased from $3.5\text{L/min} \rightarrow 6.0\text{L/min}$. At the opposite extreme, for cases where the temperature gradient was small ($T_{amb} \rightarrow 27.5^\circ\text{C}$), the trend of increased ventilation flow-rate with increased cavity-depth was observed to reach a maximum at $\delta = 50\text{ mm}$ and slowly drop off as the cavity depth was extended further.

Flow at the inlet of the hive featured an influent draft at the bottom of the inlet gap and an effluent draft at the top. The strength of the flow into and out of the hive increases as the parameter δ is increased. Figure 4.3 illustrates changes in the flow behaviour by considering velocity magnitude in the Y-direction, the direction normal to the inlet plane, plotted along the span of the inlet in the vertical direction (z-direction) when $T_{amb} = 25^\circ\text{C}$. The air exchange is weakest when $\delta = 0\text{ mm}$ and the separation of inflow and outflow occurs at approximately $z = 20\text{ mm}$, where $z = 30\text{ mm}$ represents the top of the inlet. The air exchange across the inlet is strongest

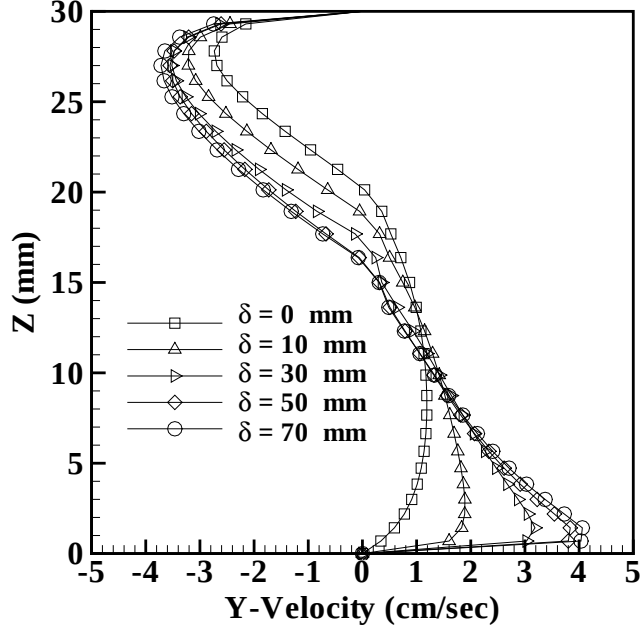


Figure 4.3: A plot of Y-velocity across the vertical span of the inlet plane for various cases of bottom board depth (δ) when $T_{amb} = 25^\circ\text{C}$

when $\delta = 70$ mm and the separation of inflow and outflow occurs at approximately $z = 16$ mm. As the depth of the bottom cavity increases, flow across the inlet is enhanced and height of the separation of inflow and outflow decreases slightly.

The amount of CO_2 generated in the hive remained relatively constant for all cases of bottom cavity depth. This is expected since the thermal input for the model are the temperature profiles applied to represent the brood, which is fixed for all cases. Considering Figure 4.4, it is interesting to note the substantial changes to the clearance efficiency of CO_2 (η) that occur as the parameter δ is varied. When the driving force for flow (ΔT) was large, the influence of bottom cavity depth on the parameter η was less pronounced – a very small increase in clearance efficiency was observed, which began to drop off slightly as δ was increased beyond 50 mm. For cases where ΔT was small, the influence of bottom cavity depth became more apparent.

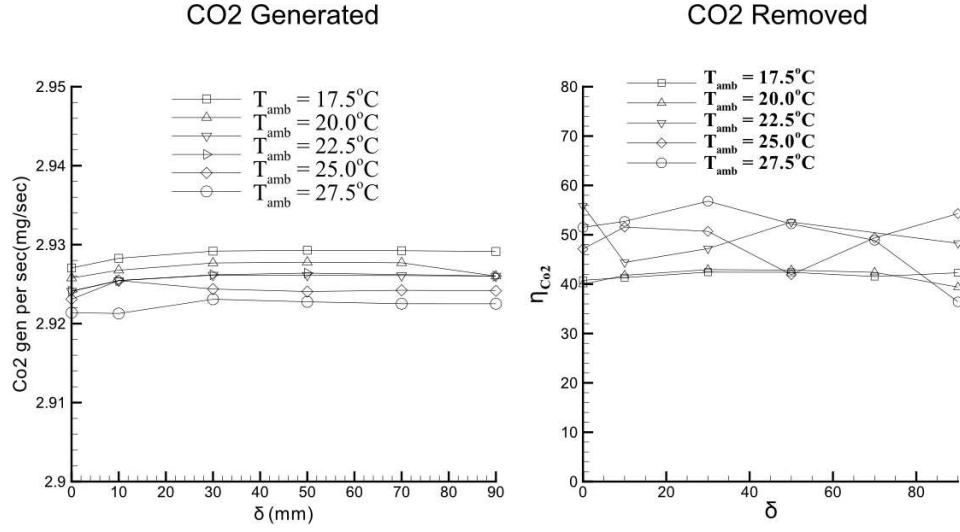


Figure 4.4: LEFT: CO_2 generated within the hive body due to bee metabolism plotted for various cases of δ at different temperatures. RIGHT: CO_2 removal efficiency (η) plotted for various cases of δ at different temperatures.

CO_2 clearance efficiency jumped from 40 $\rightarrow$ approx. 50% in most cases. Inconsistent trends were observed for clearance efficiency with variation of the parameter δ that focus around cases where $T_{amb} = 22.5^\circ C$ and $\delta = 10$ mm. The inconsistent results that arose from these cases indicate that some transition in flow behaviour tends to occur near these set-points.

Variation of bottom cavity depth also had a significant impact on the distribution flow within the hive body. Figure 4.5 depicts the distribution of CO_2 within the hive body, which changed as the depth of the bottom cavity was varied. The impact of δ variation was most pronounced for cases where $T_{amb} > 22.5^\circ C$, whereas the impact was less significant for lower values of T_{amb} . In general, when a bottom cavity was added, more CO_2 was drawn out of the bee cover region into either the honey super or the bottom cavity. In all cases the proportion of CO_2 in the brood chamber remained relatively constant. It was also observed that the addition of a bottom cavity resulted in a small shift of CO_2 from the honey super to the new cavity space. Considering the plots in Figure 4.5 a few instabilities exist that represent transition behaviours in

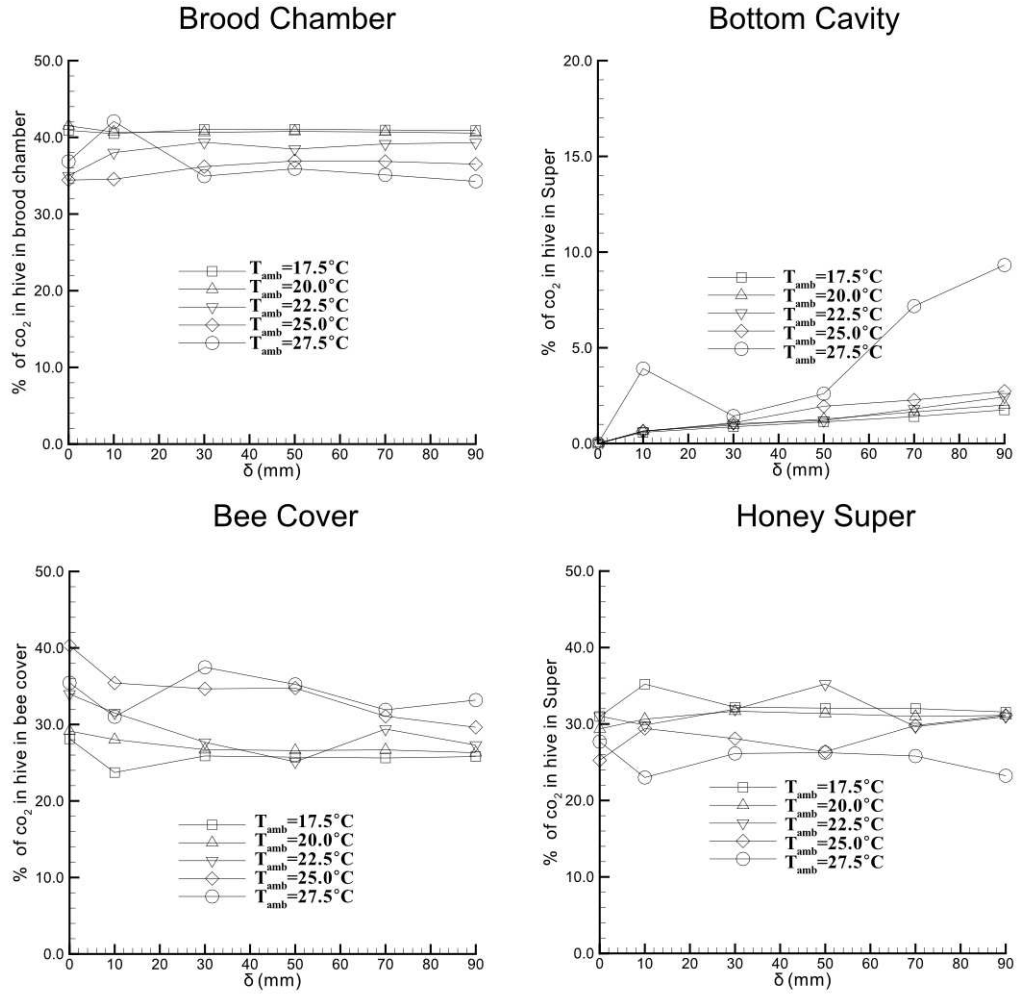


Figure 4.5: Plots of the percentage of total CO_2 within the hive body observed in different regions of the hive for various cases of bottom cavity depth (δ)

the flow field: cases where $\delta = 10$ mm experience the initial formation of the vortex at the front of the hive; cases where $T_{amb} = 27.5^\circ\text{C}$ experience a weak driving force for flow and are prone to instable flow patterns.

The change in flow within the hive imparted by the addition of a bottom cavity was confirmed by comparing the average concentration of CO_2 in different beecover volumes. Figure 4.6 reveals a general decrease in the concentration of CO_2 in Beecover #1 (the volume of bees closest to the endwall space) with increasing bottom cavity depth. Several less obvious trends were observed for Beecover #4: (1) for cases

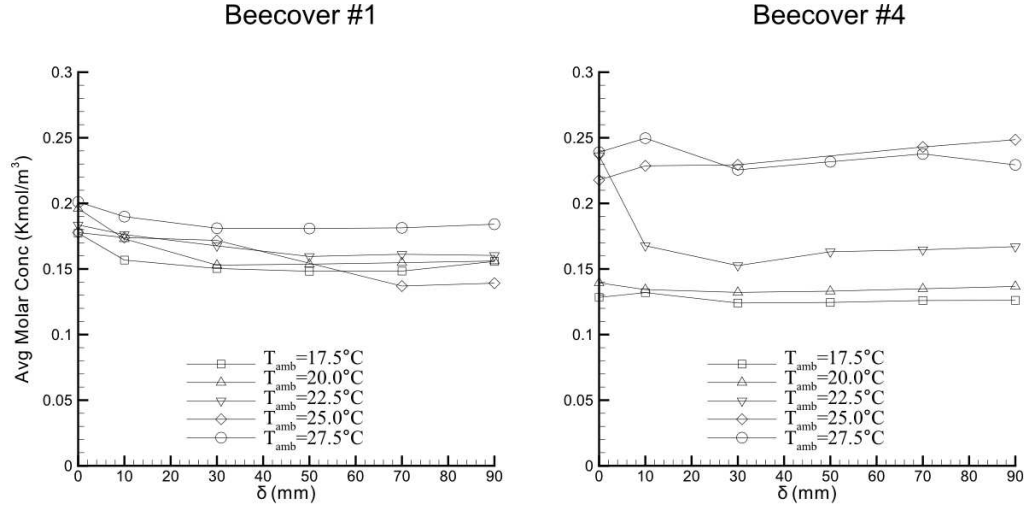


Figure 4.6: The average molar concentration of CO_2 in different Beecover volumes plotted for various cases of bottom cavity depth at different ambient temperatures. Beecover #1 is the volume of bees closest to the endwall space and Beecover #4 is the volume of bees at the centre of the hive.

where $T_{amb} < 22.5$ variation of bottom cavity depth had a negligible impact on CO_2 concentration; (2) for cases where $T_{amb} = 22.5$ the average concentration of CO_2 decreased significantly once a bottom cavity was added, and increased slightly as the depth of the cavity was increased; (3) for cases where $T_{amb} > 22.5$ adding a bottom cavity results in a slight increase in the CO_2 concentration which continues as the depth of the cavity is increased.

The amount of heat produced in the hive depends on the local temperature conditions at the brood surface. The addition of a bottom cavity results in a small increase in the amount of heat lost to air in all areas of the hive. Figure 4.7 illustrates the heat loss profile of the hive as each point represents the net heat loss for individual frame spaces (designated by beespace #1-7). The comb faces adjacent to the endwalls do not contain brood and are not included in the heat loss plot. The shape of the heat loss profile, when considered across the span of the hive, changes slightly as bottom cavity depth is increased. More heat is drawn off the centre beespace resulting in

a small spike in the plot of heat loss profile. It is important to recognize that this increase in heat lost to the air is negligible in comparison to the heat lost to the brood for incubation. However, this measure is useful to describe the changes in flow behaviour within the hive body – increased heat loss translates to increased air-flow.

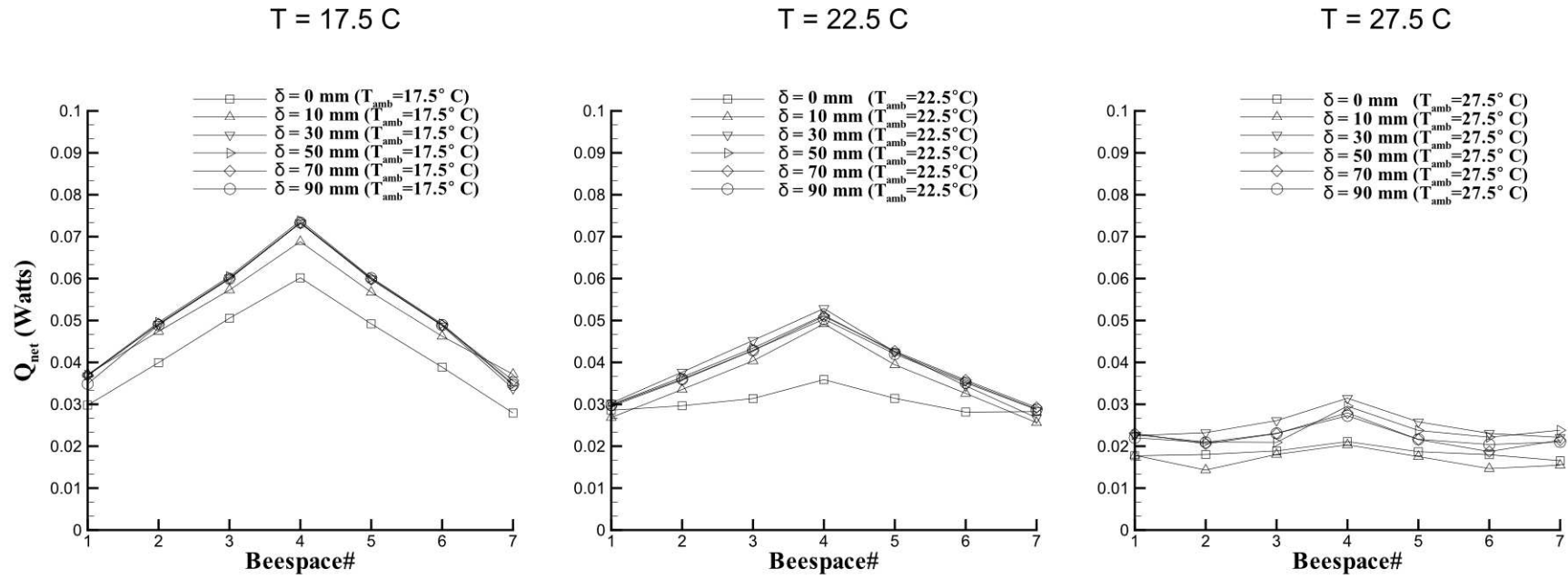


Figure 4.7: Plot of net heat lost to the air from each 'beespace' (the space between comb frames) for various cases of bottom cavity depth at a reference temperature of 25.0°C

Changes in the mixing characteristics of air within the hive body were measured using residence time or age-of-air. By comparing the residence time results from cases of different bottom cavity depth (δ), it is evident that increasing δ has an impact on the nature of flow within the hive. Figure 4.8 illustrates the age-of-air profile across the hive frames for different cases of bottom cavity depth at three different T_{amb} conditions. For cases when the temperature gradient (ΔT) is large, the residence time of air decreases moving from the endwall positions to the centre of the hive reaching a minimum of approximately 140 s. The addition of a bottom cavity had a small effect for these cases and resulted in a decrease in residence time near the end walls from 190 s when $\delta = 0$ mm to 160 s when $\delta > 10$ mm. The residence time at the endwalls began to increase again once δ was increased beyond 70 mm.

For cases when the $T_{amb} = 22.5^\circ\text{C}$ the addition of a bottom cavity served to reduce the average residence time in all regions of the hive to an approximate value of 175 s (when compared to the flat bottom cases represented by $\delta = 0$ mm). At the centre of the hive, Beespace #4, this represents a reduction of 30% in the average residence time of air. For cases where ΔT was small ($T_{amb} = 27.5^\circ\text{C}$) adding a bottom cavity deeper than 10 mm served to reduce the residence time of air in the hive in all regions slightly, with maximum reductions observed near the endwalls.

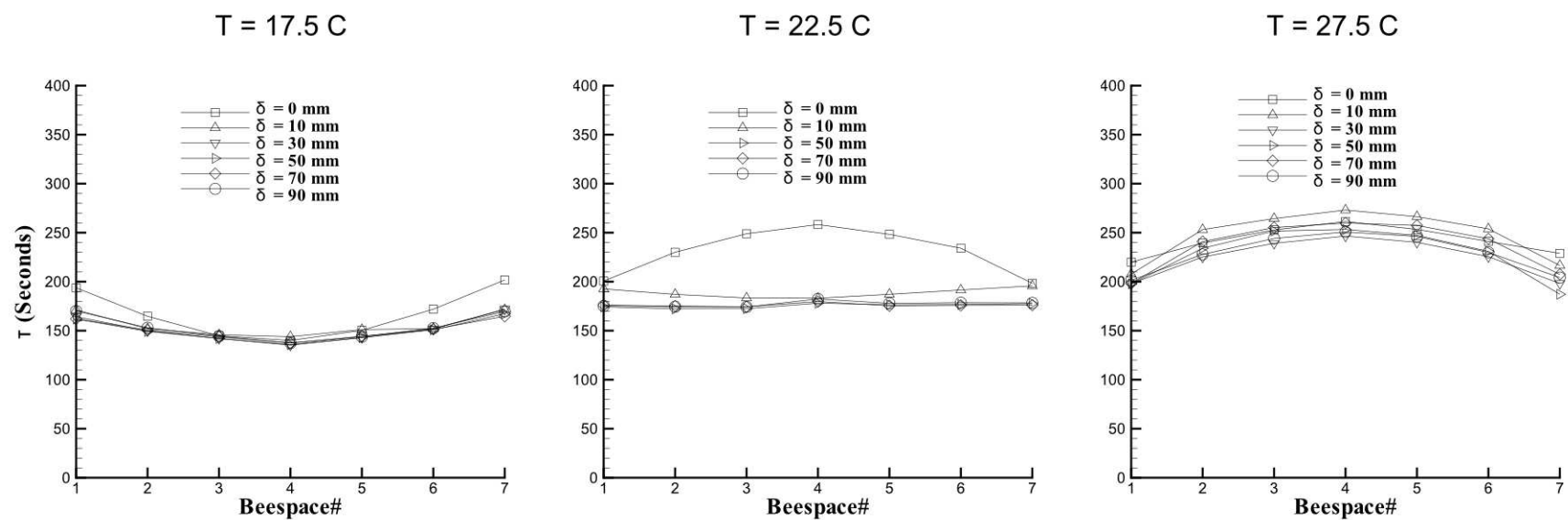


Figure 4.8: Plot of residence time of air within each 'beespace' (the space between comb frames) for various cases of bottom cavity depth at three reference temperatures: 17.5, 22.5 and 27.5 °C

Figure 4.9 illustrates the concentration of CO_2 plotted along the centre YZ-plane of the hive cavity for each rectangular bottom case - the small figure in the upper-right corner of Figure 4.9 highlights the location of the centre YZ-plane. Review of the CO_2 contours reveals a change in the concentration profile as cavity depth increases. For the purpose of discussion, we define the circular region of high CO_2 concentration as the ' CO_2 -Zone'. Without a bottom cavity ($\delta = 0$ mm) the CO_2 -Zone is noticeably skewed towards the front of the hive. The attitude of the CO_2 -Zone is tilted slightly from horizontal. CO_2 contours through the rest of the hive cavity form irregular shapes and no uniformity can be described. Without a bottom cavity ($\delta = 0$ mm) the CO_2 profile depicts higher $[CO_2]$ at the front of the hive and lower $[CO_2]$ at the back of the hive. If a bottom cavity is included CO_2 concentration takes on a stratified profile. The most uniform CO_2 profile was observed for the deepest bottom cavity case ($\delta = 90$ mm). The CO_2 -zone was noticeably centred within the cross-section of the hive and shows horizontal attitude. Also, as bottom cavity depth increases CO_2 contours through the rest of the hive cavity form stratified patterns that are nearly identical at both the front and back of the hive.

The addition of a bottom cavity has a significant impact on the nature of flow within the hive. To describe the changes in flow, graphic plots of z-velocity and y-velocity were generated to show the behaviour of flow along the inlet to each frame space. Figure 4.10 illustrates the location for where the velocity profiles were generated. Figure 4.11 and Figure 4.12 describe the air-exchange behavior between the added-bottom-cavity-space and the upper-hive-compartment at $T_{amb} = 17.5^\circ\text{C}$ and $T_{amb} = 25.0^\circ\text{C}$ respectively. For the case of a hive with no bottom cavity ($\delta = 0$ mm) air travels downward (-ve z-velocity) at the front of the hive (designated by $Y = 0$ mm) and is drawn upward (+ve z-velocity) at the back up the hive ($Y = 450$ mm). This trend was observed at the endwall locations and the centre plane of the hive. When a deep cavity is used air travels down at the back of the hive and is draw

Contours of CO₂ Concentration Plotted on Centre YZ-Plane for Rectangular-Bottom Cases of Different Cavity Depth

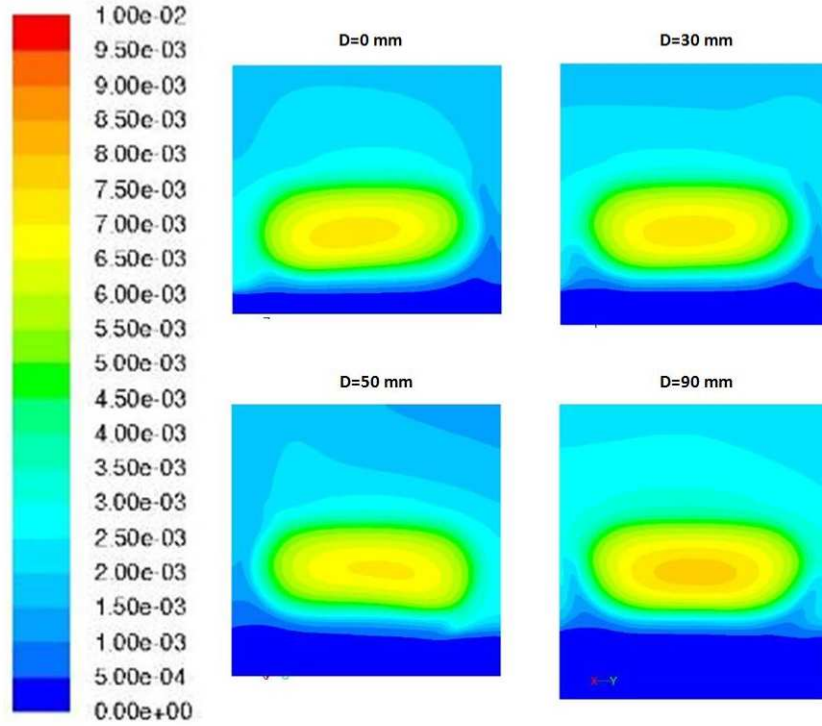


Figure 4.9: Contours of CO_2 plotted on the centre YZ-plane of the model domain for various cases of bottom cavity depth

upward near the front of the hive. In general, for cases where $T_{amb} = 17.5^\circ\text{C}$ the driving force for flow (ΔT) is large and flow is more vigorous in all regions of the hive, as denoted the the larger y-velocity values. The changes in flow behaviour that arise with the addition of a bottom cavity are more dramatic for cases where ΔT is small - bouyancy driven flow begins to dominate and z-velocity increases. A strong down draft occurs at the back of the hive when $\delta = 50$ mm and ΔT is small.

Location of Z-Velocity Plots

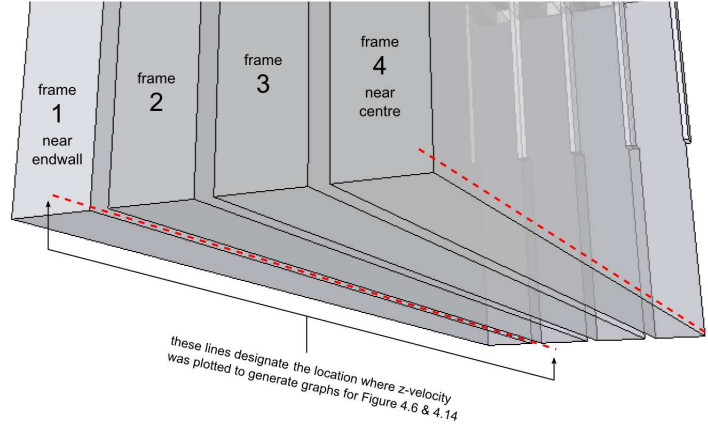


Figure 4.10: The dotted lines shown in this figure illustrate the location in the hive where z-velocity was plotted to illustrate the nature of flow. Frame 1 designates a frame close to the end wall space and Frame 4 designates a frame at the centre of the hive.

4.1.2 Experiment A Discussion

Addition of a Rectangular Bottom Cavity of Variable Depth (δ)

The marked increase in flow across the hive inlet (+70%) is the most dramatic result of the depth study. Addition of a bottom cavity clearly impacts the flow entering and leaving the hive. Changes to conditions within the hive, as indicated by local residence time, heat loss profile, concentration profiles etc., indicate that the addition of a bottom cavity also has a strong influence on flow within the hive. It is interesting to note the increased inlet air-exchange and altered flow within the hive body arise due to a general shift in the behavior of flow field within the hive. A vortex-zone is formed within the bottom cavity once it is added. In the vortex-zone, cooler (dense) air enters the hive in a stream which flows down into the bottom cavity. The cool stream of air then travels to the back of the hive where it is forced up to meet the warmer (less dense) air of the hive body. At this point the cooler air is redirected towards the front of the hive where the bulk is pushed outside again without ever penetrating the upper-hive-compartment.

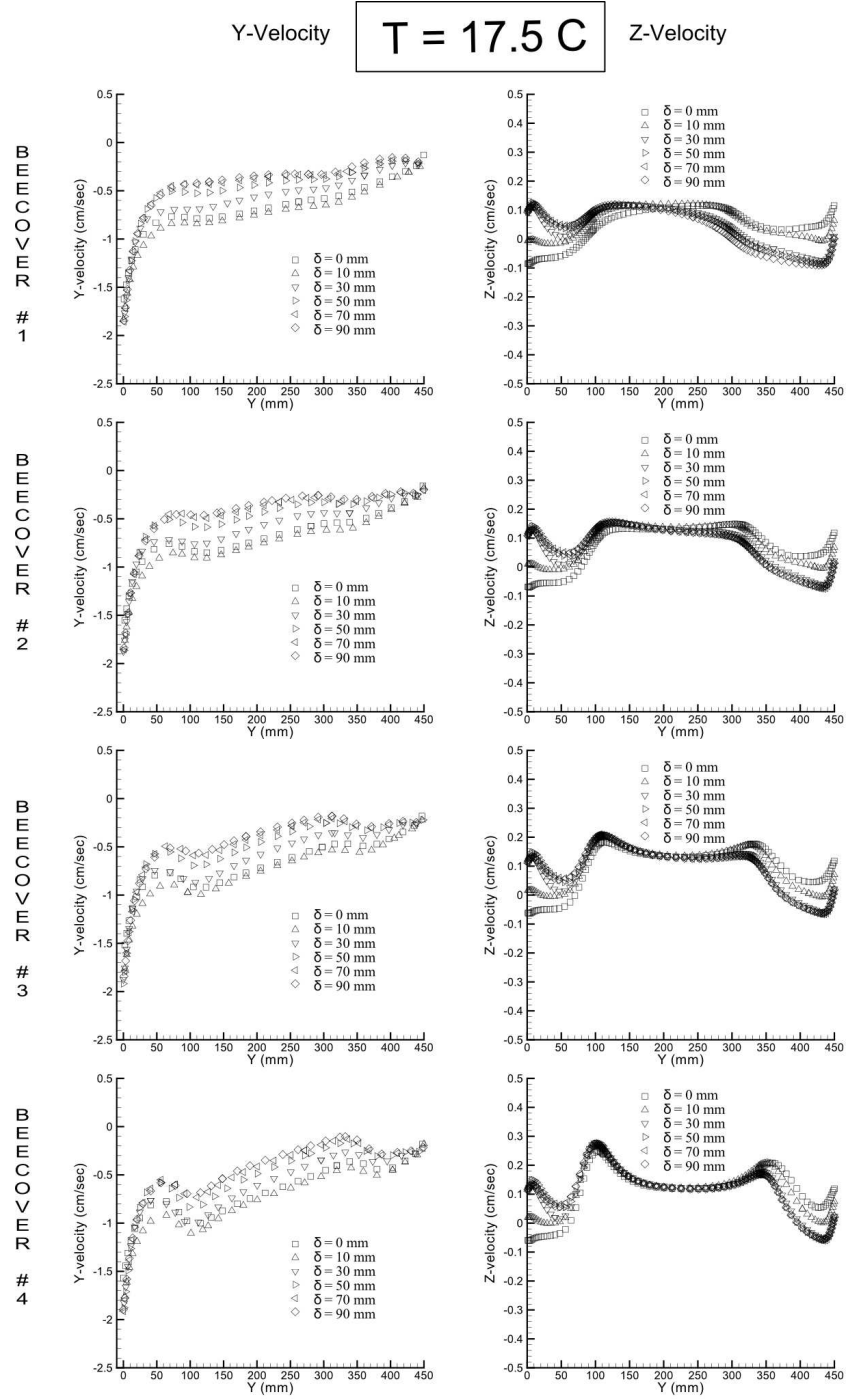


Figure 4.11: Z-velocity plotted along the Y-span of the hive at the inlet of beespaces between combs. Beespace #1 is the combspace closest to the end wall of the hive and beespace #4 is the combspace at the center of the hive. $Y = 0$ denotes the front of the hive and $Y=450$ denotes the back.

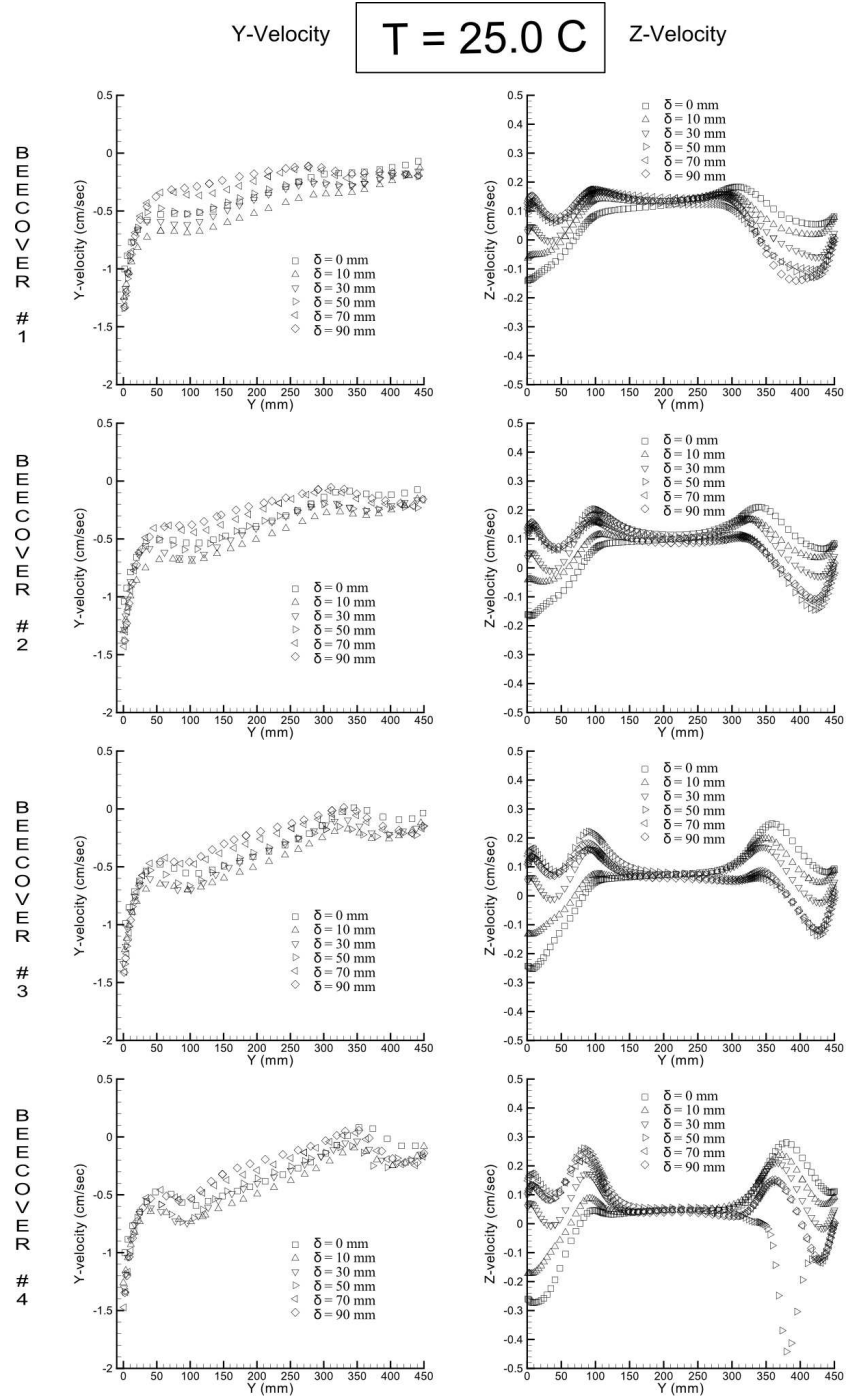


Figure 4.12: Z-velocity plotted along the Y-span of the hive at the inlet of beespaces between combs. Beespace #1 is the combspace closest to the end wall of the hive and beespace #4 is the combspace at the center of the hive. $Y = 0$ denotes the front of the hive and $Y=450$ denotes the back.

For cases when $\delta = 0$ mm (the standard, flat bottom board) fresh air entering the hive is forced into the upper hive compartment once it reaches the back of the hive, due to the limited space available for redirection. The presence of the bottom cavity beneath the level of the hive inlet greatly reduces the volume of air which directly penetrates the hive body. Instead, air exchange occurs slowly as stale hive air is drawn off by a venturi effect and fresh air is slowly drawn up to replace it. Conceivably, this could offer an advantage to honeybees who are constantly under pressure to maintain the temperature of their brood. Having a bottom cavity minimizes direct exposure of the brood to influent air, effectively buffering the internal hive environment from the external world. An implicit advantage afforded by a slow exchange between the hive and ambient environments is the increased control honeybees may exert over that exchange.

The presence of the circulation zone within the bottom cavity changes the way air circulates within the hive body. As indicated by Figure 4.8 air flow increases slightly in the end-wall regions of the hive and reduces slightly in the centre regions of the hive. Considering Figure 4.12 and Figure 4.11 completes the picture of how the flow within the hive changes as the parameter δ is increased. If a cavity is added to the bottom of the hive, the vortex-zone created causes a reversal in direction of circulation within the hive. Instead of fresh air being forced up the back of the hive, stale air is now drawn off the back of the hive and fresh air is drawn up at the front. Increasing the depth of the cavity serves to increase the strength of the flow in the vortex-zone and subsequently, the strength of flow within the hive body. However, the flow observed within the body of hives with a bottom cavity was noticeably weaker than the flow within the body of hives with the standard, flat bottom board. To understand this result, consider the newly formed vortex in the bottom cavity, which circulates vigorously. Since fresh air is no longer forced into the hive body causing displacement ventilation, and is allowed to gently meet the warm air mass within,

the hive body is not disrupted as observed in hives with flat bottoms. Instead flow in the upper hive body is 'stirred' by the gentle interaction with the vortex.

It is difficult to predict how this dramatic change in flow behaviour will influence the physical processes of the honeybee colony, however some facts can be addressed:

A vortex is created below the hive

Rate of ventilation increases

Circulation in the hive body changes significantly

Strength of flow is a function of cavity depth, δ

Strong down draft at $\delta = 50$ mm

Slow exchange of air implies improved control

4.2 Experiment B

ADDING A CURVED BOTTOM CAVITY OF VARIABLE SHAPE

4.2.1 Experiment B Results

Pathlines shaded by velocity magnitude, shown in Figure 4.13, help to illustrate the subtle changes in flow dynamics which result from the variation of the parameter α . The vortex in the front of the hive, which was observed in Experiment A, exists in the same location as before, due to the rapid descent of influent air. For front-skewed cases ($\alpha < 0.25$) the cooler, denser air entering the hive descends the front curve to the bottom of the cavity. The steep descent creates a small wave as the air rebounds off the bottom of the cavity. The characteristic wave slowly decreases in magnitude from $0.25 < \alpha < 0.50$ and the region directly above the wave becomes more uniform. Once $\alpha > 0.50$, the stream of cooler, dense air descends the bottom

cavity less aggressively, reaching the back of the hive with minimal disturbance and a higher velocity. It is also important to note that the inlet vortex is most intense for front-skewed cases and loses intensity as α progresses to back-skewed cases.

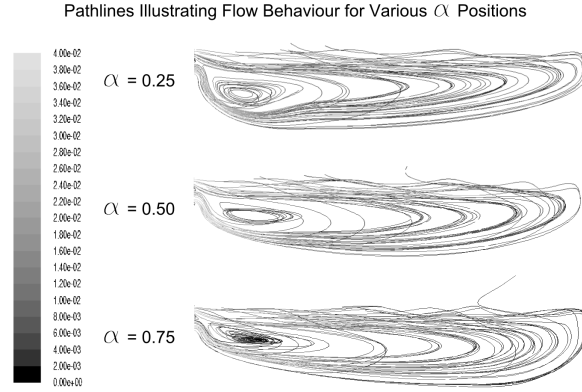


Figure 4.13: A plot of flow pathlines in the bottom cavity section of the hive for various geometries (defined by the parameter α) illustrates the differences in flow behaviour that arise due to geometry change.

In all cases, once the incoming air stream reaches the back of the hive body, it is forced up the back of the bottom cavity where it meets the warm mass of air contained in the upper-hive-compartment. The air stream is then redirected back along the bottom of the warm air-mass to the front of the hive where it is exhausted along the top portion of the inlet. For cases where the temperature gradient is relatively large ($T_{amb} = 17.5^\circ\text{C}$) changes in the flow field induced by varying the parameter α were small. For cases where the temperature gradient was small ($T_{amb} = 25^\circ\text{C}$) changes in the flow field induced by varying the parameter α were more substantial. The most significant change observed, for small ΔT cases, occurred at the back of the hive where the influent stream is forced up and meets the warm air mass of the upper-hive-compartment: flow at the back to the hive is enhanced for cases of $\alpha > 0.50$.

The exchange of air across hive inlet changes slightly with variation of the parameter α . Ventilation flow rate was highest for front skewed cases and a max flow of

6.24 L/min was observed when $T_{amb} = 17.5$. This value decreased to a minimum of 6 L/min for the extreme back-skewed cases (where $\alpha = 0.90$) representing a decrease of approximately 4%. The same trend was observed for other cases of T_{amb} as shown in Figure 4.14. The plot of ventilation flow rate also revealed an interesting result for cases where ΔT was small – ventilation flow rate peaked at $\alpha = 0.45$ and continued to decrease in the same manner as other cases of T_{amb} . To understand the break that occurred in the inlet flow rate trend for cases where the temperature gradient was small it is necessary to consider how the flow behaviour within the hive body is impacted by variation of α .

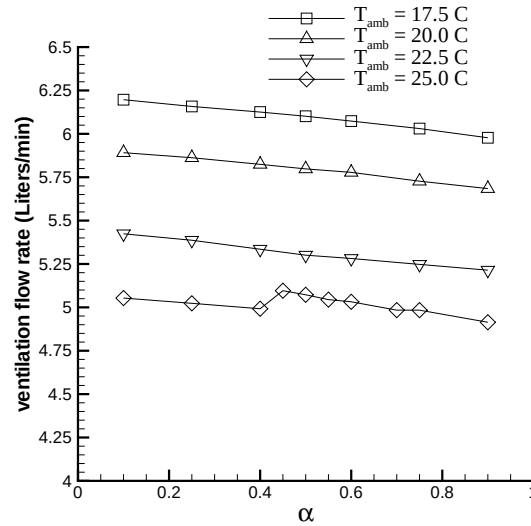


Figure 4.14: Ventilation flow rate in L/min is plotted for different α position over range of temperatures from $17.5 \rightarrow 27.5$ °C

An interesting result was observed in the measure of CO_2 clearance efficiency (η) as the parameter α was varied. For cases having a large temperature gradient (ΔT), variation of α had no significant influence on clearance efficiency. However, when ΔT is small, a change in flow behavior occurs between $0.40 < \alpha < 0.50$ and as a result, CO_2 clearance efficiency increases from 40% to 50%. A peak CO_2 clearance efficiency was observed when $\alpha = 0.60$. For all cases of T_{amb} the quantity of CO_2 generated in

the hive, which is dependent on bee metabolism, remains constant for all variations of α . Figure 4.15 describes the above noted flow features – the plot on the left presents the CO_2 generated in the hive while the plot to the right presents the CO_2 removal efficiency.

Another flow transition occurs between $T_{amb} = 20.0$ and 25.0 °C. Simulations conducted at $T_{amb} = 22.5$ °C encountered difficulty reaching convergence and grid refinement was required to advance the solutions of these cases. This result indicates a break-down of flow stability within the hive – a tendency toward unsteady behaviour. As $T_{amb} \rightarrow 25$ °C flow is re-established and removal efficiency increases as described in the previous paragraph.

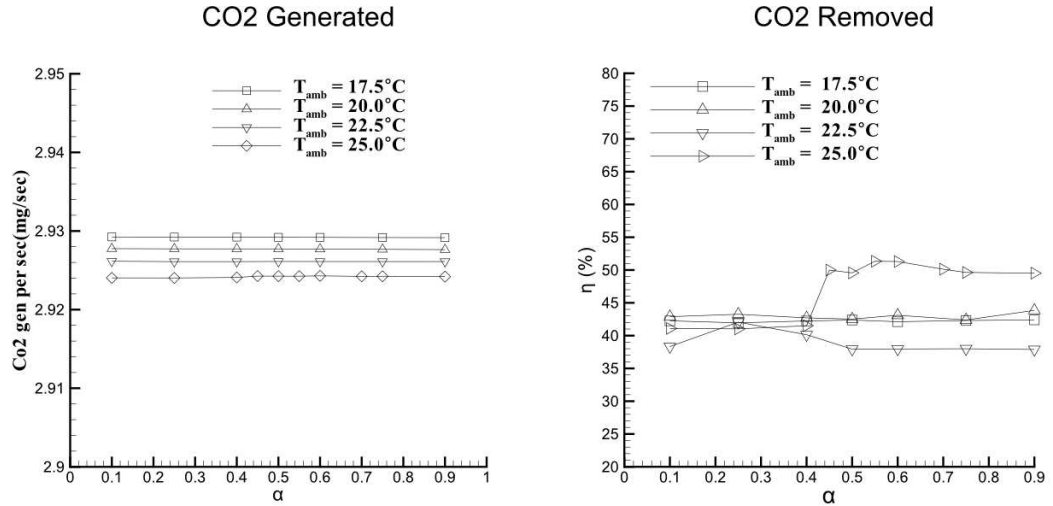


Figure 4.15: LEFT: CO_2 generated within the hive body due to bee metabolism plotted for various cases of α at different temperatures. RIGHT: CO_2 removal efficiency (η) plotted for various cases of α at different temperatures.

Figure 4.16 provides another look at the removal efficiency of CO_2 from the hive. This plot clearly indicates that the influence of α variation increases as the temperature gradient decreases. When ΔT is large, changing the cavity curvature has negligible impact on the CO_2 removal efficiency of approximately 42%. As ΔT decreased, variation of the parameter α began to have a stronger effect on η – flow tended

to decrease slightly when $T_{amb} = 22.5^\circ\text{C}$ and as T_{amb} increased beyond 22.5°C front skewed cases remained around $\eta = 40\%$ efficiency while back-skewed cases jumped to around $\eta = 50\%$.

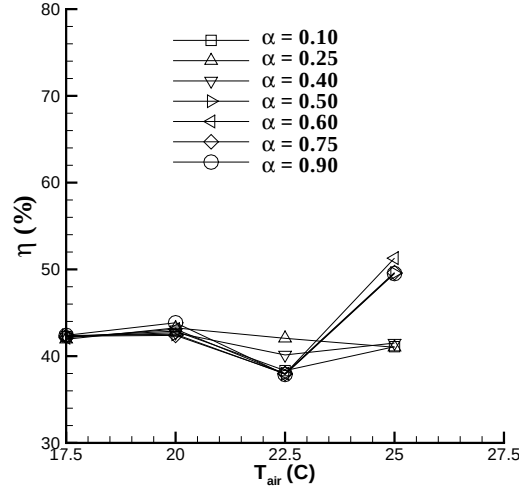


Figure 4.16: The removal efficiency of CO_2 plotted at various temperatures for various cases of α

Varying the parameter α did not have an influence on heat loss trends for individual brood spaces for cases when ΔT was large, but did have an interesting impact on the heat lost profile for cases when ΔT was small. Figure 4.17 illustrates the total heat loss observed for each individual beecover that is present in between comb frames, in the same fashion as Experiment A. Two different temperature cases are presented: the left plot illustrates the minimal impact of α variation observed for large ΔT cases; the right plot illustrates the interesting change in flow behaviour arising due to α variation for small ΔT cases. A shift in the heat loss profile of the hive occurs when $\alpha > 0.50$. For cases where $\alpha < 0.50$ (front-skewed cases) the heat loss profile observed resembles that observed using the standard, flat-bottom board ($D=0$ mm)(refer to Figure 4.7). When $\alpha > 0.50$ (rear-skewed cases) the new profile observed indicates that more heat is lost to the air at the centre of the hive as well as

the endwall regions while minima occur in the in the spaces adjacent to the centre.

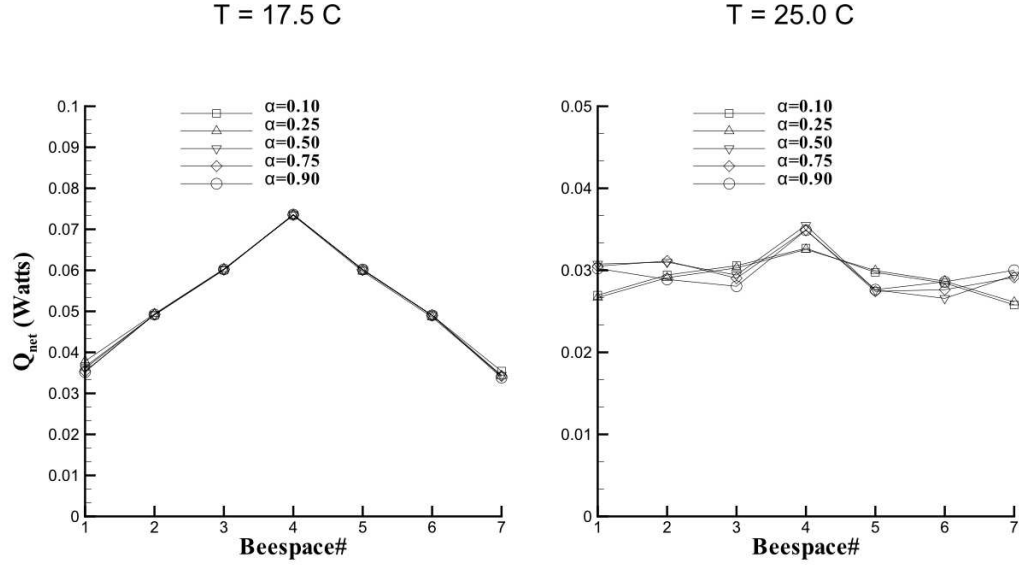


Figure 4.17: Plot of net heat lost to the air from each ‘beespace’ (the space between comb frames) for various cases of α position at a reference temperature of $25.0\text{ }^{\circ}\text{C}$

The hive environment undergoes a change in nature of flow within the hive body when the apex of curvature (α) varies. The change in flow behaviour is illustrated in Figure 4.18 which shows the residence time of air in different regions of the hive to create a profile of residence time. Again, two extreme cases for T_{amb} are presented to illustrate the contrasting nature of large versus small ΔT cases. As before, when ΔT is large, the impact of α variation is negligible. The impact of α variation was significant for caases where Δ was small. A threshold was observed at $\alpha = 0.50$ which separates mixing behaviour within the hive body into two distinct groups: when $\alpha < 0.5$ (front-skewed cases) the residence-time-profile resembles an inverted “V” with a sharp peak in the centre of the hive and linear trends to the endwalls; when $\alpha > 0.50$ (rear-skewed cases) the residence-time-profile resembles an inverted “U” with a smooth curve from endwall to endwall reaching a gradual peak in the centre of the hive. By comparison, rear-skewed cases result in slightly longer residence time in the centre of the hive than front-skewed cases (265 versus 248 seconds), while

the regions closer to the endwalls experience significantly shorter residence time (150 versus 190 seconds).

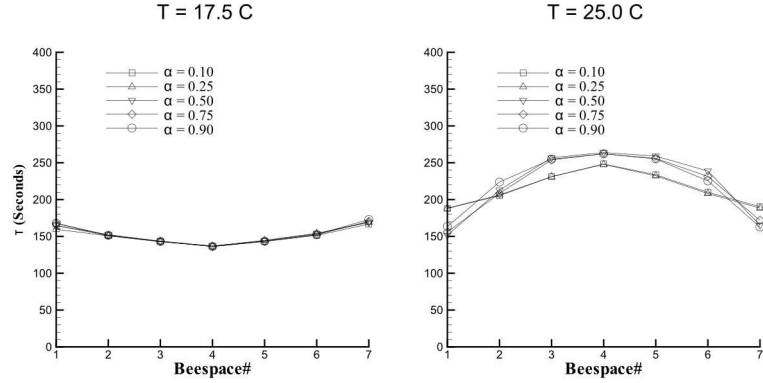


Figure 4.18: Average residence time of air is plotted at different locations in the hive (designated by beecover number) for different α positions at 17.5 and 25.0 °C

To better understand the nature of the flow change which occurs when α moves from a front-skewed position to rear-skewed, it is useful to consider the distribution of CO_2 within the hive. Figure 4.19 illustrates the average concentration of CO_2 in different regions of the hive and the total mass of CO_2 in the hive at 17.5 and 25 °C. Again, when ΔT is large, the impact of α variation was negligible on the distribution of CO_2 in the hive body. When α was shifted from front-skewed positions to back-skewed positions, CO_2 was shifted from the bee cover regions into the honey super. Also, the mass of CO_2 in the hive increased slightly when α shifted to back-skewed cases.

In order to determine the impact of flow changes induced by alpha variation, environmental conditions within the hive need to be addressed. The concentration of CO_2 was plotted along the centre YZ-plane of the hive body for various values of α , in the same manner as described in Experiment A. Review of the CO_2 contours pictured in Figure 4.20 reveals a change in the concentration profile as the parameter α is varied. The nature of this change is representative of the impact that new

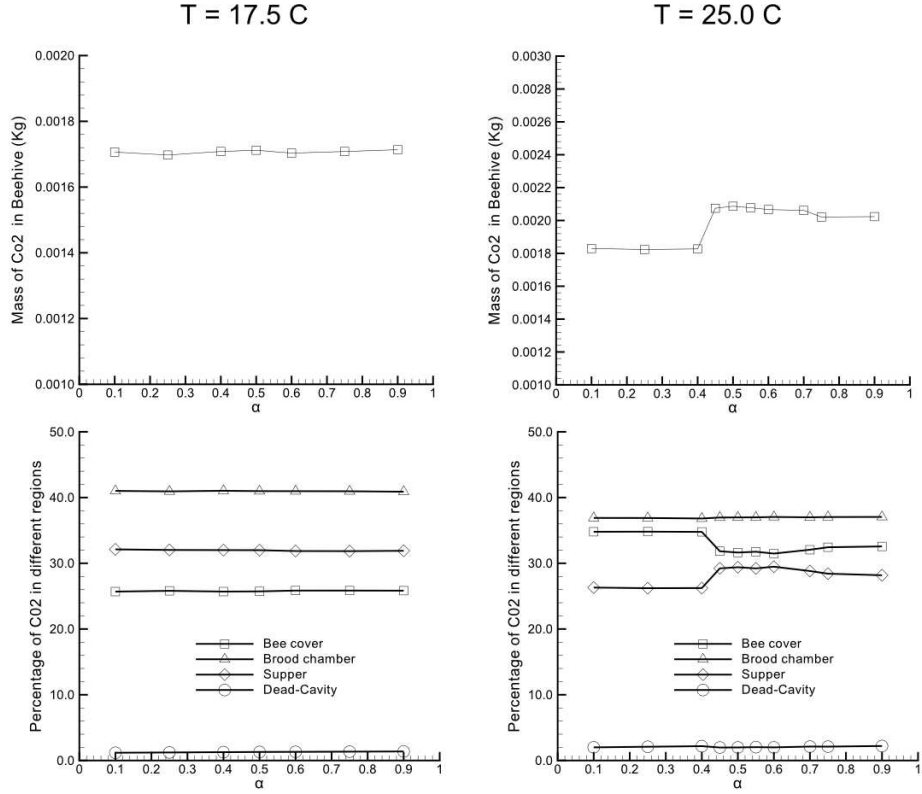


Figure 4.19: The total mass of CO_2 in the hive body and the distribution of CO_2 within different regions of the hive body plotted for various cases of α positions.

flow patterns have on conditions within the hive. Most notable are the shape and position changes of the ellipsoidal shaped region of high CO_2 concentration. This area represents the exhaust of bee metabolism within the beehive and shall be termed the *brood-signature* to facilitate discussion.

For front-skewed cases ($\alpha < 0.50$) the brood-signature is noticeably skewed towards the back of the hive. The attitude of brood-signature is tilted slightly from horizontal. CO_2 contours through the rest of the hive cavity form a somewhat stratified profile; however the uniformity of this profile is skewed, and higher concentration of CO_2 is observed at the back of the hive. For rear-skewed cases ($\alpha > 0.50$) CO_2 concentrations shift to a stratified profile. The most uniform CO_2 profile was observed when $\alpha = 0.75$. The brood-signature is noticeably centred within the cross-section

and has a horizontal attitude. CO_2 contours through the rest of the hive form increasingly stratified patterns as $\alpha \rightarrow 0.75$.

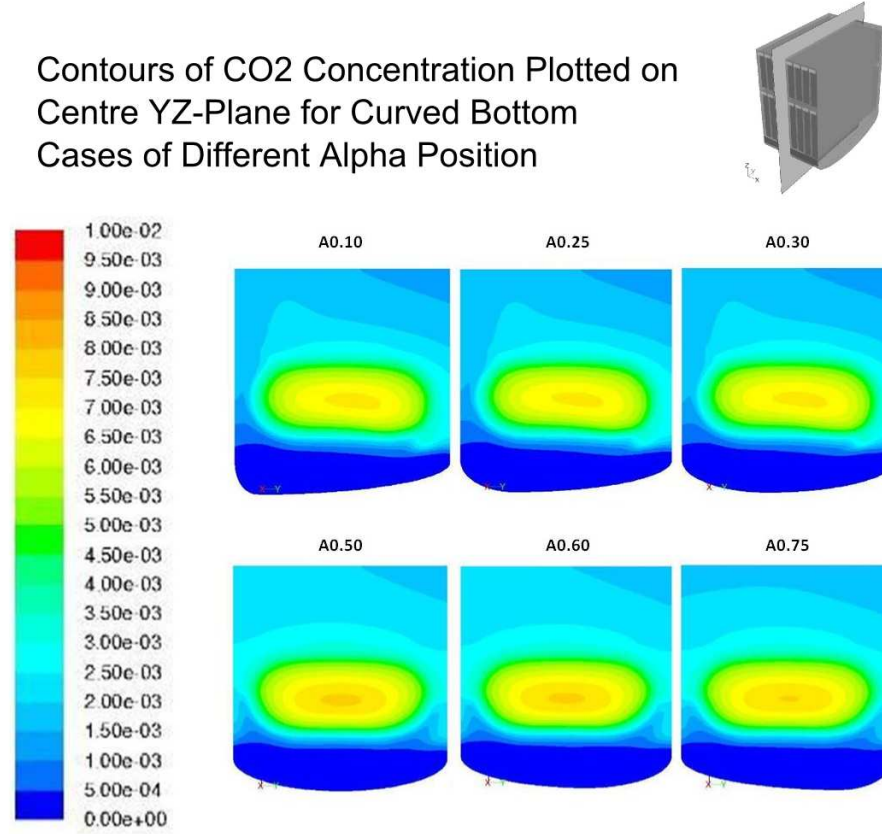


Figure 4.20: Contours of CO_2 plotted on the centre YZ-plane of the model domain for various cases of α position

As discussed previously, variation of the parameter α did not have a significant impact on the nature of flow within the hive when the temperature gradient driving the flow was large. Figure 4.21 illustrates the air-exchange behavior between the added-bottom-cavity and the upper-hive-compartment for cases where $T_{amb} = 17.5^\circ C$, in the same manner as described earlier in Experiment A. It is clear from these plots that variation of the parameter α had very little influence on the nature of flow in the hive when the ΔT is large.

Figure 4.22 describes the flow behaviour for cases where ΔT was small, which

had a significant response to variation of the parameter α . For all cases where α was varied, air travels downward (-ve z-velocity) at the back of the hive and travels upwards (+ve z-velocity) at the front of the hive. This was true at the centre and endwall positions for all cases. Along the endwall position there was very little change in direction and magnitude of flow with variation of the parameter α . A significant result occurred along the centre position of the hive (designated by Beespace #4) for front-skewed cases. Flow behaviour at the back of the hive changed dramatically - a large down-draft occurs at the back of the hive for front-skewed cases. For all rear-skewed cases a much weaker downdraft occurs at the back of the hive in the centre region.

4.2.2 Experiment B Discussion

The addition of a curved bottom cavity resulted in subtle changes to flow behaviour within the hive. Variation of the parameter α created front-skewed and back-skewed curves of varying degree and the flow fields generated by each group were significantly different. Front-skewed cases caused cool air to drop quickly to the bottom near the front of the hive, resulting in slight flow instability and the formation of a wave. As $\alpha \rightarrow 0.5$ this slight shock wave diminishes. Back-skewed cases caused cool air to slowly descend to the bottom, resulting in a smooth flow. The transition of flow behaviour that occurs at $\alpha = 0.5$ has a significant influence on hive performance. Although ventilation flow rate remains constant for all α 's, CO_2 clearance efficiency jumps at $\alpha = 0.5$. Since, for all cases, no change occurs in the quantity of air moving into and out of the hive nor in the amount of CO_2 generated, the concentration of CO_2 in the effluent air stream must increase when $\alpha > 0.5$. Therefore, mass transfer processes within the hive are affected and as a result more CO_2 is moved into the exhaust stream before it exits. An interesting change in flow behaviour occurs at the back of the hive when the parameter α crosses the 0.5 threshold for cases when ΔT is

small. For front-skewed cases, a significant downdraft occurs at the back of the hive and for rear-skewed cases the draft does not occur. What is most interesting is that the flow conditions at the front of the hive remain static for all values of α . By this measure, variation of the parameter α has influence on distribution of flow within the hive body.

It is difficult to predict how this subtle change in flow behaviour will influence the physical processes of the honeybee colony, however some facts can be addressed:

Vortex size and strength depends on α

Rate of ventilation changes slightly

Greater changes in flow behaviour occur when ΔT is small

Flow transition occurs at $T_{amb} = 22.5^\circ\text{C}$

4.3 Comparison of Experiment A and B

In order to assess the influence of hive modifications, consider the geometries modeled in the present work in relation to the flat bottom standard. In Experiment A the standard flat bottom board was replaced by a bottom cavity of variable depth (δ). In Experiment B the rectangular bottom cavity was altered to take the shape of a half-ellipse of variable apex position (α). The modifications to the depth of the bottom cavity appears to have a more significant impact on the nature of hive flow than modifications to the shape of it. The results of Experiment A and B support the notion that varying bottom cavity depth has a strong influence on the flow behaviour within the hive, while varying the bottom shape seems to have a more subtle influence on the nature of flow within the hive body.

Both the results of Experiment A and Experiment B revealed that adding a bottom cavity to the standard hive and modifying its characteristics (depth and shape

in the present case) had more substantial impacts on the flow in the hive when the temperature gradient between the hive and the ambient environment (ΔT) was small. This is significant as hive ventilation becomes increasingly important as ambient temperatures increase. The presence of a bottom cavity appears to offer a passive means of increasing ventilation and circulation, specifically when ambient temperatures are high.

Considering the heat loss profile and residence time profile for Experiments A and B in relation to the flat bottom case, it appears that more flow is directed around the cluster rather than into it if a bottom cavity is present on the hive that is more than 10 mm deep. This is evident due to the lower residence time observed and lower concentration of CO_2 observed near the end wall locations when δ is increased. In Experiment B it was shown that this effect is further enhanced by shaping the bowl to a curve and fixing the parameter α to rear-skewed cases. Although the variation of α represented only a single, simple shape modification the results of Experiment B demonstrate promising potential for shape optimization.

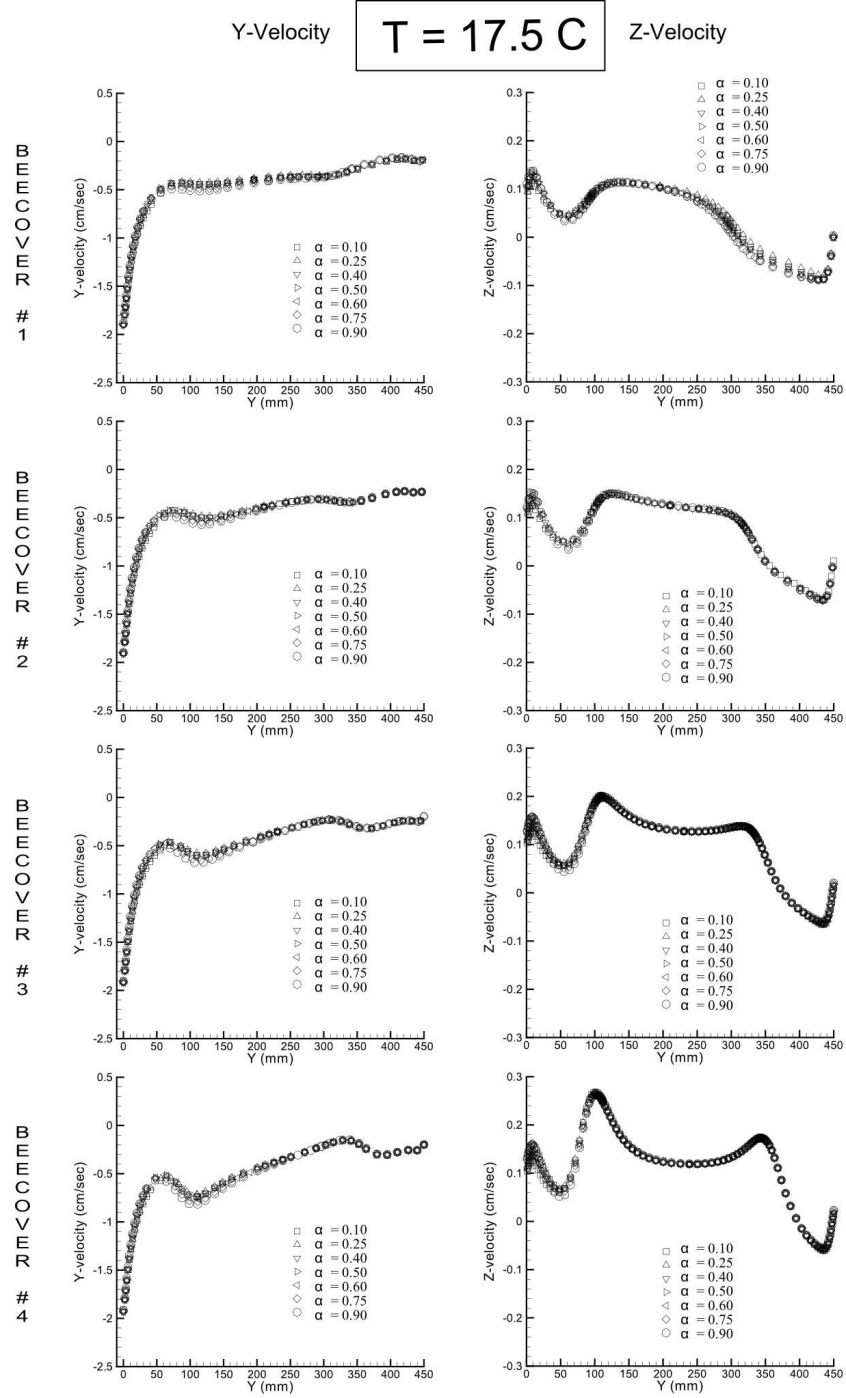


Figure 4.21: Z-velocity is plotted along the span of the hive in the Y direction at the inlet of beespace between combs for various cases of α position. Beespace #1 represents the combspace closest to the end wall of the hive and beespace #4 represents the combspace at the center of the hive. $Y = 0$ represents the front of the hive and $Y = 450$ represents the back of the hive.

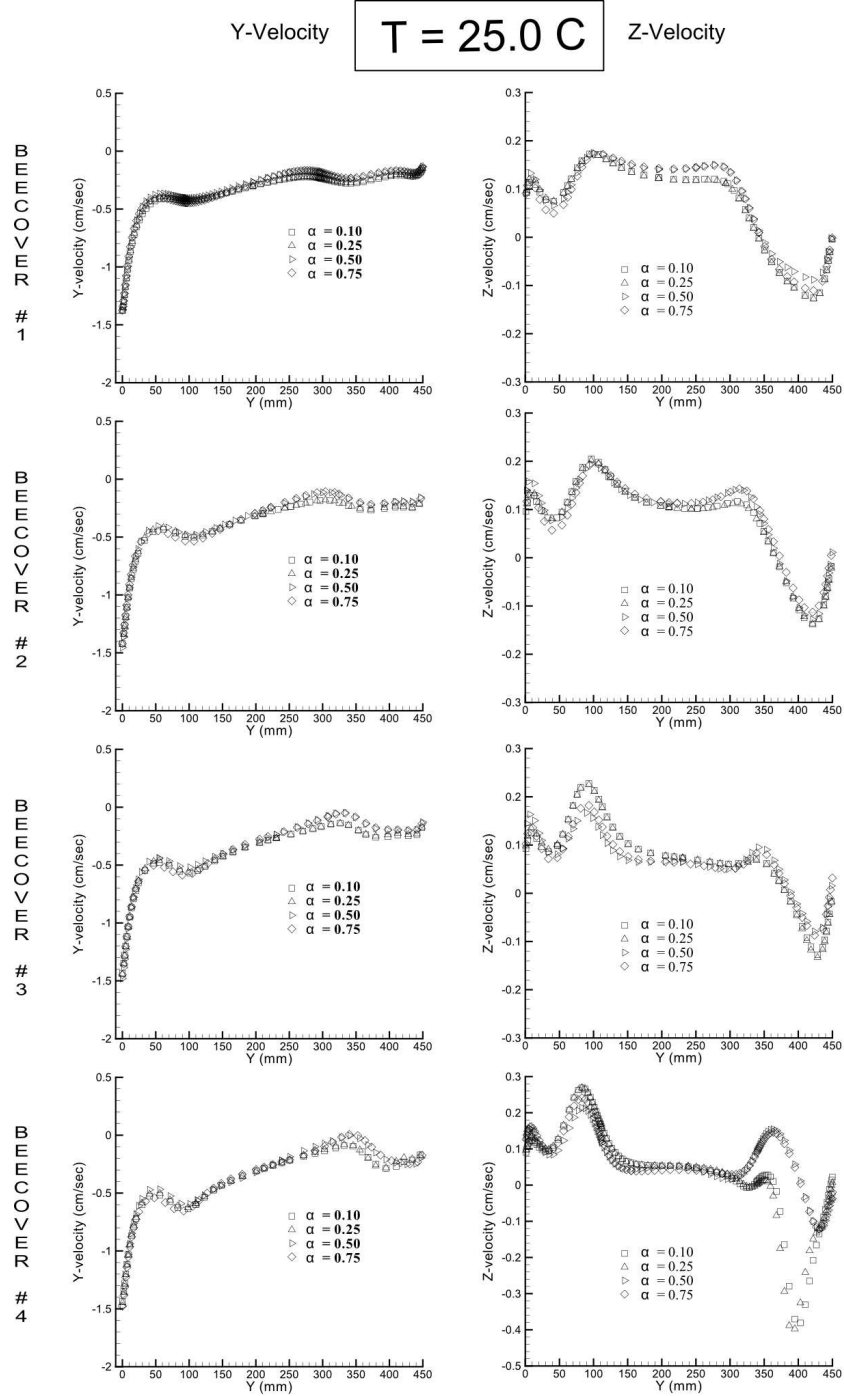


Figure 4.22: Z-velocity is plotted along the span of the hive in the Y direction at the inlet of beespace between combs for various cases of α position. Beespace #1 represents the combspace closest to the end wall of the hive and beespace #4 represents the combspace at the center of the hive. $Y = 0$ represents the front of the hive and $Y = 450$ represents the back of the hive.

Chapter 5

Conclusions

5.1 Changes to Bottom Board Geometry

The present work represents an initial step into the use of CFD to study optimization of honeybee hive design. In this preliminary investigation, simple changes were made to the standard hive geometry and flow within the hive was simulated under different temperature conditions. The results of the two series of experiments performed indicate a strong relationship between the geometry of a honeybee hive and the behaviour of flow within it.

5.1.1 Influence of bottom cavity depth

Prior to this study, the concept of a bottom cavity below the inlet has not been discussed in literature. The idea to add a cavity beneath the existing hive body was derived from consideration of the natural nest, which typically has this feature. From the results of this study, it is clear that adding a bottom cavity creates a completely new flow regime within the hive body. Most notably, a vortex forms near the front of the hive as cold air circulates in and back out rapidly. The results of this study suggest that an optimal bottom cavity depth could be determined; however, the model must

be refined to better represent the conditions in an actual beehive before a definitive optimization study can be performed with confidence. The steps to refine the model in order to complete a proper optimization study are outlined in Section 5.3.

5.1.2 Influence of cavity shape

The influence of bottom board shape (as considered in this work) on the physical processes within a standard honeybee hive is less substantial than the influence of bottom board depth. Variation of the bottom board shape appears to impart subtle control over the nature of flow within the hive body. Considering that the shape for this study and the method of its variation were arbitrarily chosen, the results cannot be considered definitive in terms of their description of bottom board shape performance. Many studies must be carried out to characterize various shape modifications in a systematic fashion, similar to the present method. However, the results indicate a strong potential for the optimization of an ideal bottom board shape. Studies of this nature would require careful integration of honeybee fanning behaviour and other hive processes that have not been treated in this study.

5.2 Hive Economy

For bees, it takes honey to maintain their society. The energy required for the normal metabolism of bees is exclusively supplied by their conversion of sugars which they obtain from stockpiled honey. Bees work hard to seek out and collect nectar, and evaporate the thin liquid into dense honey - all these processes are driven by bee metabolism, which is fueled by honey. Many other tasks are performed by bees to maintain their habitat and their colony – all tasks require energy and again, that energy comes from stored honey.

So how can a bottom board improve the lives of bees? From an energetics stand-

point, any energy that can be saved on one task can be reserved for another. If a simple change in hive geometry can impact the hive environment in a way that improves hive efficiency, then such a change should reduce the thermodynamic-pressure on bees to actively maintain their environment. For example, if a new bottom board resulted in increased ventilation, it is expected that fewer bees would actively engage in fanning behaviour (an energy intensive process) – time and energy are conserved.

Conservation of time and energy by bees is of vital importance to beekeeping as an industry. Bees are under constant pressure to actively promote hive health and stability. They spend time and energy to fight off illness and maintain brood. Having more “unemployed” bees available to take up tasks and more energy with which to drive them implies an increase in the resources available to colony. As a secondary advantage, less time and energy devoted to hive tasks translates to fewer resources consumed as well as more time and energy available for the collection of more resources – an improvement to the economy of the colony and ultimately, the beekeeper. Finally, the honey ripening process has not been included in the beehive models created to date, yet the results indicated that ventilation and circulation in the hive are improved by the presence of a bottom cavity. If this improvement translates to an increase in the production of honey, an optimized bottom board could prove extremely useful to the beekeeping economy.

5.3 Future Work

What is most clear, in reflection of our hive model studies to date, is the fact that many gaps exist in the quantitative description of honeybee hives. Honeybees have long inspired the curiosity of scientific minds and many have studied their many behaviours in painstaking detail, as highlighted in Section 2. Yet the dynamic workings of the hive as a whole remain superficially understood. Several areas of research re-

quire immediate attention in order to supplement the studies performed to date and develop the field of computational apiculture. The following topics describe potential improvements to the present work along with suggested studies to develop the resources available to this field of study.

5.3.1 Moisture transport and honey drying

The current investigation neglects the influence of moisture exchange on flow within the hive. This is a significant simplification since the process of honey ripening involves the evaporation of water from the dilute nectar, which foraging bees collect and deposit inside empty cells of the honey super. By the time nectar has condensed into honey, it has given up a large volume of water to the hive environment. Water content in nectar varies a great deal depending on plant species and geographic location. Some plants produce thick nectar (tending towards sap) while others produce nectar having a water content as high as 80%, which must be reduced to around 20% to become honey [15]. Honeybees have been shown to express preference for hive humidity around 75% [8], while the constant flux of moisture from the nectar stores work to increase hive humidity. Therefore excess moisture from the honey ripening process must be expelled through passive and/or active ventilation to maintain the desired set point.

Our first study revealed that air circulation in the hive depends on both heat and mass transfer processes, and it is reasonable to assume that the inclusion of moisture transport in the hive model will have a significant impact on both the resultant energy and mass balance. The position of the honey super above the brood chamber (which is also found in the natural nest [41]) implies that fresh (relatively dry) air warms as it must pass through or around the hot brood cluster before reaching the nectar drying region above. The fresh air mass will then lose energy as it picks up water by evaporation. The air mass will tend to increase in density by two mechanisms: by

picking up moisture and losing energy. Considering the physics of mass transfer, the now stale air mass will be driven downward due to an amplified density gradient. By this logic, the inclusion of moisture transport in the existing model would serve to strengthen the existing flow pattern.

To simulate the transport of moisture from the comb cells of the honey super, a mathematical description of the ripening process must be defined. Honeybees fill the honey super starting at the top row and progressively working downward as the cells fill. Once a cell of ripened nectar is full, the bees cap the cell with wax and continue to fill the lower rows of the comb. In commercial beekeeping, empty honey supers are added below existing supers as they are filled. Therefore, to obtain a reasonable model of moisture transport from honey ripening, one should consider fully ripened, capped honey exists at the top of the honey super ($\dot{n}_{H_2O} = 0$) and fully unripened, uncapped nectar exists at the bottom of the honey super ($\dot{n}_{H_2O} = MAX$). In this way a ripening gradient is defined that dictates moisture source and energy sink terms, which can be applied as boundary conditions on the comb surfaces of the honey super.

5.3.2 Fanning Activity

One of the most visible displays of active environmental control performed by bees is grouped fanning. On hot summer days in warmer climates bees often gather at their hive inlet, arranged in ordered groups, to actively supplement the natural ventilation of their hive. Bees anchor themselves to their hive, engage their flight muscles, and work as a synchronized team to draw air from the hive and sometimes to push air into it. As highlighted in Chapter 2.3, many studies have looked into the triggers for fanning response, yet the influence of fanning activities on the hive environment has not been measured in detail. CFD offers a unique opportunity to study the hive environment using quantitative analysis, however care must be taken to ensure an accurate model is created.

Including the effect of active fanning by groups of bees at the hive entrance could be accomplished by applying a velocity profile to the inlet of the hive. Several methods could be used to construct an accurate velocity profile for this purpose. Using advanced anemometers and a carefully designed experimental setup a profile could be generated taking measurements directly from the hive. Care would be necessary to ensure that the fanning activities are not disrupted. Another approach to defining a velocity profile for the hive inlet would be to consider the fanning behaviour of a single bee and groups of bees, respectively. In this way, indirect measurements of fanning behaviour can be used to develop a model for the inlet velocity profile based on number and position of fanning bees.

5.3.3 Traditionally standard geometries

The results of this investigation suggest a significant relationship between the geometry of a honeybee hive and the patterns of air circulation within it. Considering that the present work was limited to modifications of the bottom board depth and shape, an immense wealth of additional geometric configurations remain to be simulated. The traditional roots of beekeeping and the hereditary nature of the practice have spawned many variations to the hive and its operations (some more successfully than others). Modifications which are prevalent in the beekeeping community are:

Top ventilation hole Many beekeepers use top ventilation holes of various shapes and sizes to facilitate honey ripening, especially in hot climates. This type of modification provides a means for displacement ventilation which greatly increases the volume of air flow through the hive body.

Modified brood chamber openings Some beekeepers modify the openings of their hives by placing additional entrance holes/slots at various locations on the brood chamber. Devices can be purchased to modify the hive to create additional

openings, and CFD can be used to evaluate their performance.

Slotted bottom board In warm climates, slotted bottom boards are used by some beekeepers to improve hive ventilation with the goal of reducing swarming behaviour. These devices would significantly alter the boundary conditions of the hive environment and would no doubt impart significant changes to the nature of flow within the hive body.

Other hive geometries Many other hive modifications exist which vary by region and beekeeping tradition. CFD offers a unique means to critically evaluate hive modifications using parameters that are relevant to honeybee welfare.

5.3.4 Wintering conditions and strategies

The wintering condition of honeybees in cold climates is very important to beekeepers. Many studies have focused on wintering and airflow has been determined to play an important role in the survival of honeybees over winter. CFD is ideally suited to study the wintering conditions of bees and the model would prove far more simple to develop than the present work due to the relative inactivity of the hibernating colony. Different techniques are used by beekeepers to assist their wintering colonies, however the main theme is to add insulation around the hive body. Often the entrance slot is reduced to a small gap and some keepers add extra vents in various places. A collection of photos show-casing the features of a typical winter hive setup in South-Western Ontario is presented in Figure 5.1 The evolution of wintering strategies comes from the experience and creative intuition of beekeepers. Very little quantitative information is available to evaluate the influence of winter modifications on the hive environment.

A comprehensive winter hive study would be extremely useful to the beekeeping community. First an extensive survey of wintering techniques and technologies must

WINTERING SETUP

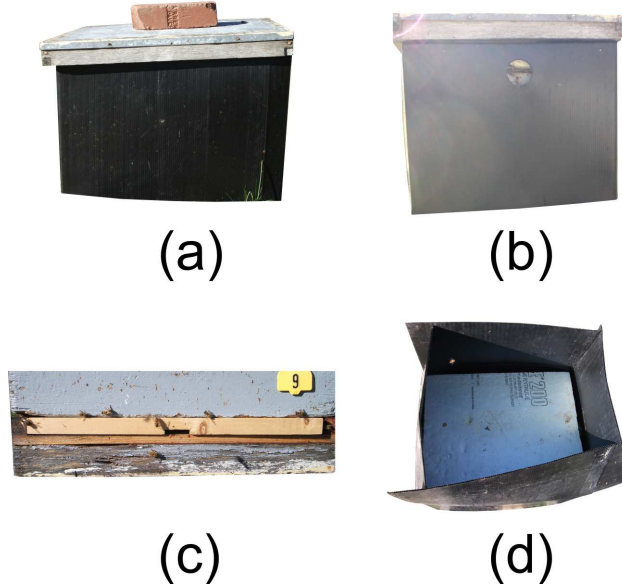


Figure 5.1: (a) the hive is reduced to one brood chamber for wintering and is covered with corrugated plastic - air space is maintained between the plastic and the hive body. (b) an opening in the plastic cover is positioned at the front of the hive above the inlet height. (c) the hive entrance is reduced to a small opening using a block of wood. (d) a sheet of insulation is placed on top of the hive beneath the plastic cover.

be completed to determine a subset of cases to study. The mathematical models to predict thermal profiles within wintering bee clusters that were developed in past research[34] can be used to define the thermal boundary conditions for the wintering cluster in CFD simulations. The hive simulation tool that was created for our first simulation study (and adapted for the present work) can be easily modified to accommodate the wintering setup. For wintering, the hive is reduced to a single brood chamber box with a reduced inlet. Wintering colonies have no brood and the entire population of bees cluster around the queen to keep her warm over winter. The cluster moves to the top of the hive and does not move much over the course of winter.

Some commercial beekeepers, typically in more extreme-cold climates, choose to winter bees indoors. Indoor beekeeping involves careful consideration of ventilation and many strategies are employed by beekeepers for this purpose [18]. This presents

yet another set of circumstances to consider for wintering. Yet, the conditions of indoor wintering are easy to incorporate into a theoretical model due to mechanical control exercised over the indoor environment.

5.3.5 Natural nest cavities

The natural habitat of honeybees remains a scarcely documented subject since feral beehives are typically difficult to find. Despite this fact, the published information on tree hives is sufficient to enable the development of a generalized, natural nest model. Several important differences exist between the natural and commercial hive configuration, as highlighted in Chapter 1. A comparison of the physical processes within the natural nest and those within the commercial standard could present some unique perspectives on honeybee ecology. In particular, the results of the present study indicate a strong correlation between hive geometry and air flow behaviour within. Also, our first study revealed a similar correlation with respect to brood size and position and the air flow behaviour within the hive cavity. Therefore, it is reasonable to assume that the layout of the natural nest would generate a considerably different flow scenario than that observed for the commercial standard.

To facilitate the development of a realistic tree hive model, more extensive surveys of tree hives are required. A display tree hive was created by beekeepers at an apiary in Southwestern Ontario out of a tree cavity that was cut in an 8 foot section. A honeybee colony was introduced and thrives within the tree hive. This prototype is ideally suited for experimental purposes. An ideal tree hive could be created by boring a large log to create a model tree cavity. The model tree cavity can be rigged with extensive sensor networks, observation and sampling ports, and modular modifications. In this way, a wealth of organizational and environmental data on the natural tree hive can be collected with high resolution and control.

Results from research into tree nest cavities can be compiled and used as input for a

CFD model. Computer simulations offer a unique ability to study environments which are otherwise unmeasurable, making it ideal to investigate the physical processes within a natural tree hive. A better understanding of natural hive operation could offer valuable insight into the management of commercial bees.

5.3.6 Detailed brood description

The CFD work performed on honeybee hives to date suggests that the shape, size, and position of the brood play an important role in defining the flow behaviour in the hive body. The brood photo study conducted within the scope of our research was not carefully designed any many uncontrolled variables were noted. However, the results from those visual observations revealed interesting trends in the development of the brood throughout the season. It is recommend, in order to further the state of mathematical apiculture, that a comprehensive brood survey be undertaken to quantify the shape, size and position of the brood and other hive contents in a scientific manner.

Most importantly, new hives should be used to survey the brood to ensure that standardized results are obtained. The hives used in our previous field study were old and inconsistent. In many cases, open holes were visible through the seams between hive chambers which would create drafts and influence the nature of flow in the hive. In is essential that the experimental hive influence the behaviour of bees as little as possible. In this way, an accurate picture of how the bees arrange the contents of their hive can be created, considering changes to the organization over the span of a full season.

5.3.7 Advanced data collection

There is an immediate need for detailed, quantitative data on the thermoregulatory behaviour of honeybee colonies and the collective management of hive ventilation.

Sensor and imaging technologies rapidly improve and through creative effort, information gaps regarding the behaviour of bees within a closed hive can be filled. Challenges facing the collection of data from closed honeybee hives include:

- small space available for internal measurements,
- disruptive nature of honeybees,
- cost and availability of quality instrumentation,
- significant sampling resolution required for suitable 3D data,
- seasonal limitations of studying honeybees.

To overcome these and other challenges, time and resources must be allocated. An immense wealth of knowledge can be gained from CFD simulations of honeybee hives, as many operating scenarios can be considered using theoretical models to produce very precise results. However, without sufficient accurate data for use as model input or for use in model validation, representative model results cannot be expected.

Advanced technologies would facilitate the collection of real-time, high resolution hive data. The use of infrared and x-ray imaging could aid in the collection of honeybee position data. Advanced fiber-optic devices (anemometers and temperature sensors) should be used to collect air velocity and temperature data at various hive locations, but most importantly at the hive inlet. Automated data collection should be used to streamline the collection of data and minimize the number of interruptions to the hive required to take measurements.

5.3.8 Transient Model

The beekeeping industry stands to benefit significantly from the development of a working hive model capable of transient simulations. This tool could be used to

test the efficacy of many hive devices and operational strategies. Specifically the use of bio-control agents, usually in the form of spore-laden powder, are growing in popularity for the treatment of certain bee illnesses. A fully integrated, transient hive model would be extremely useful in the evaluation of dosing techniques or devices. To develop a complete hive model, the various hive functions highlighted above which were not treated in this study must be compiled with care.

Bibliography

- [1] ANSYS INC. *Fluent 6.3 User's Guide*, 2006.
- [2] BASAK, T., AND RAO, K. K. A model for heat transfer in a honey bee swarm. *Chem. Eng. Sci.* 51, 3 (1996), 387–400.
- [3] BAUM, K. A., RUBINK, W. I., PINTO, M. A., AND COULSON, R. N. Spatial and temporal distribution and nest site characteristics of feral honey bee (hymenopter: Apidae) colonies in a coastal prairie landscape. *Environmental Entomology* 34, 3 (2005), 610–618.
- [4] BAYTAS, A. Thermal non-equilibrium natural convection in a square enclosure filled with a heat-generating solid phase, non-darcy porous medium. *Int. J. Energy Res.* 27 (2003), 975–988.
- [5] BAYTAS, A. C., AND POP, I. Free convection in a square porous cavity using a thermal nonequilibrium model. *International Journal of Thermal Sciences* 41 (2002), 861–870.
- [6] CAHILL, K., AND LUSTICK, S. Oxygen consumption and thermoregulation in apis mellifera workers and drones. *Comp. Biochem. Physiol.* 55 (1976), 355–357.
- [7] CRAILSHEIM, K., STABENTHEINER, A., HRASSNIGG, N., AND LEONHARD, B. Oxygen consumption at different activity levels and ambient temperatures in

- isolated honeybees(hymenoptera:apidae). *Entomologia Generalis* 24, 1 (1999), 1–11.
- [8] ELLIS, M. B., NICOLSON, S. W., CREWE, R. M., AND DIETEMANN, V. Hygro-preference and brood care in the honeybee (*apis mellifera*). *J. Insect Physiology* 54 (2008), 1516–1521.
- [9] ERGUN, S. Fluid flow through packed columns. *Chemical Engineering Progress* 48, 2 (1952), 89.
- [10] FEHLER, M., KLEINHENZ, M., KLUGL, F., PUPPE, F., AND TAUTZ, J. Caps and gaps: a computer model for studies on brood incubation strategies in honeybees (*apis mellifera carnica*). *Naturwissenschaften* 94 (2007), 675–680.
- [11] FREE, J. B., AND SIMPSON, J. The respiratory metabolism of honey-bee colonies at low temperatures. *Entomology experimental and applied* 6 (1963), 234–238.
- [12] GAMBINO, P., HOELMER, K., AND DALY, H. Nest sites of feral honey bees in california, usa. *Apidologie* 21 (1990), 35–45.
- [13] GASKELL, D. R. "An Introduction to Transport Phenomena in Materials Engineering". "Macmillan Publishing Company", New York, 1992.
- [14] GOBIN, D., AND GOYEAU, B. Natural convection in partially porous media: a brief overview. *International Journal of Numerical Methods for Heat and Fluid Flow* 18, 3/4 (2008), 465–490.
- [15] HARMAN, A., AND GARCEAU, S. *The ABC and XYZ of Bee Culture: An Encyclopedia Pertaining to the Scientific and Practical Culture of Honey Bees*, 41st ed. A.I. Root Co., 2007.

- [16] HEINRICH, B. The mechanisms and energetics of honeybee swarm temperature regulation. *Journal of Experimental Biology* 91 (1981), 25–55.
- [17] HUMPHREY, J., AND DYKES, E. Thermal energy conduction in a honey bee comb due to cell-heating bees. *J. Theor. Biol.* 250 (2008), 194–208.
- [18] KELLY, P. Personal conversation on wintering honeybees with director of university of guelph beelab, November 2010.
- [19] KLEINHENZ, M., BUJOK, B., FUCHS, S., AND TAUTZ, J. Hot bees in empty broodnest cells: heating from within. *J. Experimental Biology* 206 (2003), 4217–4231.
- [20] KOVAC, H., STABENTHEINER, A., HETZ, S. K., PETZ, M., AND CRAILSHEIM, K. Respiration of resting honeybees. *Journal of Insect Physiology* 53 (2007), 1250–1261.
- [21] KOVAC, H., STRABENTHEINER, A., AND BRODSCHNEIDER, R. Contribution of honeybee drones of different age to colonial thermoregulation. *Apidologie* 40 (2009), 82–95.
- [22] KRONENBERG, F., AND HELLER, H. C. Colonial thermoregulation in honey bees (*apis mellifera*). *J. Comp. Physiology* 148 (1982), 65–76.
- [23] LAGE, J. L. The fundamental theory of flow through permeable media from darcy to turbulence. In *Transport Phenomena in Porous Media* (1998), D. B. Ingham and I. Pop, Eds., Pergamon, Oxford, pp. 1–30.
- [24] LANGSTROTH, L. L. Beehive. *United States Patent Office Patent No. 9300* (1852).

- [25] LEMKE, M., AND LAMPRECHT, I. A model for heat production and thermoregulation in winter clusters of honey bees using differential heat conduction equations. *J. Theor. Biol.* 142 (1990), 261–273.
- [26] LENSKY, Y. Comportement d’une colonie d’abeilles a des temperature extremes. *Ins. Physiology* 10 (1964), 1–12.
- [27] LIAQAT, A., AND BAYTAS, A. C. Numerical comparison of conjugate and non-conjugate natural convection for internally heated semi-circular pools. *International Journal of Heat and Fluid Flow* 22, 6 (2001), 650–656.
- [28] MAETERLINCK, M. *The Life of the Bee*. University Press, Cambridge, 1901.
- [29] MURALIDHAR, K., AND SUZUKI, K. Analysis of flow and heat transfer in a regenerator mesh using a non-darcy thermally non-equilibrium model. *International journal of heat and mass transfer* 44, 13 (2001), 2493–2504.
- [30] MYERSCOUGH, M. A simple model for honeybee temperature regulation in honeybee swarms. *J. theor. Biol.* 162 (1993), 381–393.
- [31] NAGY, K. A., AND STALLONE, J. N. Temperature maintenance and co2 concentration in a swarm cluster of honey bees apis mellifera. *Comp. Biochemistry and Physiology* 55A (1976), 169–171.
- [32] NIELD, D. A., AND BEJAN, A. *Convection in porous media*. Springer-Verlag, N.Y., 2006.
- [33] OLDROYD, B. P. What’s killing american honey bees? *PLoS Biology* 5, 6 (2007), 1195–1198.
- [34] OMHOLT, S. W. Thermoregulation in the winter cluster of the honeybee, apis mellifera. *J. Thoeretical Biology* 128 (1987), 219–231.

- [35] OMHOLT, S. W., AND LONVIK, K. Heat production in the winter cluster of the honeybee, *apis meuifera*. a theoretical study. *J. theor. Biol.* 120 (1986), 447–456.
- [36] PETZ, M., STABENTHEINER, A., AND CRAILSHEIM, K. Respiration of individual honeybee larvae in relation to age and ambient temperature. *J. Comp. Physiol. B* 174 (2004), 511–518.
- [37] SCHMOLZ, E., DEWITZ, R., SCHRICKER, B., AND LAMPRECHT, I. Energy metabolism of european (*apis mellifera carnica*) and egyptian (*a. m. lamarckii*) honeybees. *Journal of Thermal Analysis and Calorimetry* 65 (2001), 131–140.
- [38] SCHMOLZ, E., HOFFMEISTER, D., AND LAMPRECHT, I. Calorimetric investigations on metabolic rates and thermoregulation of sleeping honeybees (*apis mellifera carnica*). *Thermochimica Acta* 382 (2002), 221–227.
- [39] SCHMOLZ, E., KOSECE, F., AND LAMPRECHT, I. Energetics of honeybee development isoperibol and combustion calorimetric investigations. *Thermochimica Acta* 437 (2005), 39–47.
- [40] SCHMOLZ, E., LAMPRECHT, I., AND SCHRICKER, B. A method for continuous direct calorimetric measurements of energy metabolism in intact hornet (*vespa crabro*) and honeybee (*apis mellifera*) colonies. *Thermochim. Acta* 251 (1995), 293–301.
- [41] SEELEY, T., AND MORSE, R. A. The nest of the honeybee (*apis mellifera* l.). *Insectes Sociaux* 23, 4 (1976), 495–512.
- [42] SEELEY”, T. D. *The wisdom of the hive : the social physiology of honey bee colonies*. Harvard University Press, Cambridge, Mass., 1995.

- [43] SEELEY, T. D., AND BUHRMAN, S. C. Nest-site selection in honeybees: how well do swarms impliment the 'best-of-n' decision rule? *Behavioral Ecology and Sociobiology* 49 (2001), 416–427.
- [44] SHAPAREW, V. Ventilation requirements of a beehive in winter. *Canadian Beekeeping* 9, 7 (1981), 105–112.
- [45] SHAPAREW, V. Wintering results using ventilating inner covers. *Gleanings in Bee Culture* (November 1982), 610–612.
- [46] SHAPAREW, V. Ventilating inner cover for beehives. *U.S. Patent*, 4483031 (November 1984).
- [47] SOUTHWICK, E. E. The honey bee cluster as a homeothermic superorganism. *Comp. Biochemistry and Physiology* 75A, 4 (1983), 641–645.
- [48] SOUTHWICK, E. E. The colony as a thermoregulating superorganism. In *he Behaviour and Physiology of Bees* (1991), L. J. Goodman and R. J. Fisher, Eds., C.A.B. International, London.
- [49] SOUTHWICK, E. E., AND MORITZ, R. F. A. Social control of air ventilation in colonies of honeybees, *apis mellifera*. *J. Insect Physiology* 33, 9 (1987), 623–626.
- [50] STABENTHEINER, A., AND CRAILSHEIM, K. The effect of activity level and ambient temperature on thermoregulation in isolated honeybees(hypemoptera:apidae). *Entomologia Generalis* 24, 1 (1999), 13–23.
- [51] STABENTHEINER, A., VOLLMANN, J., KOVAC, H., AND CRAILSHEIM, K. Oxygen consumption and body temperature of active and resting honeybees. *Journal of Insect Physiology* 49 (2003), 881–889.
- [52] STARKS, P. T., AND GILLEY, D. C. Heat shielding: A novel method of colonial thermoregulation in honey bees. *Naturwissenschaften* 86 (1999), 438–440.

- [53] STIPP, D. Flight of the honeybee. *Fortune* 156, 5 (September 2007).
- [54] SUDARSAN, R., THOMPSON, C., KEVAN, P., AND EBERL, H. Mathematical model to study ventilation in a industrial beehive during mild summer days.
- [55] SUMPTER, D. J. T., AND BROOMHEAD, D. S. Shape and dynamics of thermoregulating honey bee clusters. *J. theor. Biol.* 204 (2000), 1–14.
- [56] TAUTZ, J. *The Buzz about Bees*. Springer-Verlag, Berlin, 2008.
- [57] WATMOUGH, J., AND CAMAZINE, S. Self-organized thermoregulation of honeybee clusters. *J. Theoretical Biology* 176 (1995), 391–402.

Appendix A

Supplimentary Materials

Beekeeper Survey *Colony Ventilation Computer Simulation Study*

Contact: *Cody Thompson ~ cthompso@uoguelph.ca*

Project Background

Project Objective:

To better understand the dynamics of heat transfer and air flow within the cavity of a traditional, Langstroth, honeybee hive through use of Computational Fluid Dynamics modeling.

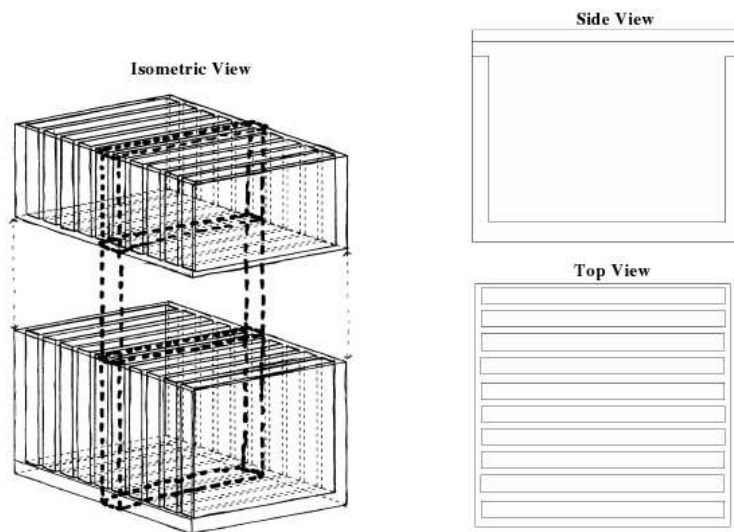
Survey Objective:

To complete the model, all relative components of the nest must be considered. Literature which references the shape of the colonies brood region is not adequate. In order to supplement our research, we would appreciate the input from local beekeepers with respects to the shape of the brood commonly observed.

Survey Questions

Our computer simulations considers one brood chamber box and one honey super box, characteristic of spring conditions.

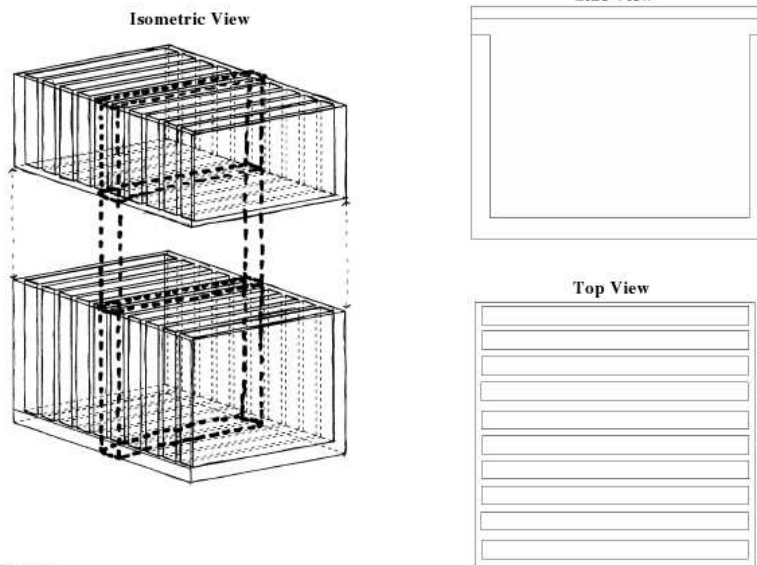
Q1 – What shape of brood do you commonly observe within the brood chamber during early season? (Use the images below to sketch the shape, and include words as necessary)



PLEASE SCAN AND RETURN TO CODY THOMPSON AT: cthompso@uoguelph.ca
OR BY MAIL AT: 1252 ALDERSBROOD ROAD, LONDON, ONTARIO, N6G4T5

Q1 Notes:

Q2 – What shape of brood do you commonly observe within the brood chamber during mid season? (Use the images below to sketch the shape, and include words as necessary)



Q2 Notes:

PLEASE SCAN AND RETURN TO CODY THOMPSON AT: cthompso@uoguelph.ca
OR BY MAIL AT: 1252 ALDERSBROOD ROAD, LONDON, ONTARIO, N6G4T5