# Beehive Ventilation: We Need to Know More and Do Better

> "Beekeepers universally agree that ensuring sufficient ventilation is vital for sustaining a thriving, healthy honey bee colony. Despite this fact, surprisingly little is known about the ventilation and flow patterns in beehives."
>
> (Sudarsan, Thompson, Kevan, & Eberl, 2016)

We do know some things about beehive ventilation, we know bees ventilate their hives to control three factors, temperature, humidity, and carbon dioxide (Southwick & Moritz, 1987).We know that by 'ventilation' we mean both interior air circulation and an exchange of interior and exterior air. We know that brood rearing, nectar processing, and winter clustering have different ventilation needs. We know that bees control ventilation by fanning, they increase in-hive airflow by sending bees outside the hive where they beard, and when necessary, they bring in water to cool the interior by evaporation (Mandl Stabentheiner, & Kovac, 2004).

We know that, outside the hive, air temperature, humidity, sunlight, rain, and wind vary a lot over the course of a day, a season, and a year. And yet, in spite of these changes outside the hive, bees maintain a stable nest environment for their brood, process nectar into honey, and maintain a viable winter cluster.

What we do not know is how much energy bees devote to ventilation and, if ventilation were to be automatically adjusted so as to require minimal effort on the bees' part, how much surplus energy the bees would have and what they would do with it. What if there are times when half the colony is working at hive ventilation and we could reduce that to almost nothing by providing some shade and a screened inner cover? Might they become healthier and more productive? These questions would seem to be worth investigating.

## What Existing Research Tells Us

Research tells us that workers who perform nest ventilation are 2 to 3 weeks old, which means that the time and effort they spend ventilating is time away from brood rearing and nectar processing (Cook, Brent, & Breed, 2017). Research also tells us about optimal in-hive levels of carbon dioxide, temperature, and humidity, and how bees control them.

### Carbon Dioxide

Honey bees have carbon dioxide ($CO_2$) receptors on their antennae (Stange, & Diesendorf, 1973). The normal atmospheric level of carbon dioxide is 0.04%, i.e., 4/100 of 1%. Bees respond to $CO_2$ levels by fanning when the level reaches 1%. (Seeley, 1974). Bees cannot sense oxygen levels. The ability to sense $CO_2$ must offer bees some survival advantage, yet the frequency that bees initiate fanning owing to elevated levels of $CO_2$ would seem to be rare, with the possible exception of times when hives are sealed, or nearly sealed, by winter snows, and the actual frequency of $CO_2$-activated fanning is unknown.

## Temperature

Honey bees detect temperature with thermoreceptors on their antennae. Considering brood, brood chamber, honey super, and winter cluster spaces, it appears that brood temperature has received a lot of attention, and the other spaces almost none.

It is well-known that bees maintain their brood at temperatures of 33-35°C. We need not discuss that point further here. It is also the case that foragers must warm up their flight muscles to at least that temperature to begin foraging (Seeley, 2010). To warm the brood, and themselves, bees consume honey and flex their flight muscles. When it is necessary to cool the brood, bees first fan and then bring in and evaporate water. Both warming and cooling the brood take an effort. It seems reasonable then, to take as a first assumption that optimal brood chamber temperature would be near, yet slightly lower than, brood temperature.

When bees are processing nectar into honey by evaporating water from it, lower relative humidity and higher vapor pressure deficits are desirable, and warming the air enhances these effects. Yet wax begins to soften at brood temperatures and melts at 62°C, so it seems reasonable that maximum honey super temperature would be a few degrees warmer than brood chamber temperature, but not so high that the weight of the stored honey would begin to collapse the softened comb.

In winter, bees begin to cluster at 14°C and become too stiff to move around 7°C. To warm the cluster bees consume honey and isometrically contract their thoracic muscles to generate heat. A winter cluster of bees can keep itself warm at very low temperatures, but if it is so cold that the cluster cannot move to access its honey stores, it risks starvation. When overwintering bees indoors, the optimal temperature range is said to be 4-7°C (Sammataro & Avitabile, 2011), so that would seem to be a good guess for optimal hive temperature when the bees are clustered in outdoor hives.

## Humidity

Honeybees have hygroreceptors on their antennae that detect relative humidity and vapor pressure deficit (*vapor pressure deficit* is a measure of how much more water the atmosphere can hold, when saturated, than it currently holds) (Ellis, 2008). Within the hive, optimal humidity may vary depending on the bees' activity. Brood cells, brood nest, honey super, and winter cluster area, each need to be considered.

Honey bee eggs require high humidity, a minimum of 55% even to hatch, and do best at 90-95%. (Doull, 1976). Also, the reproductive success of Varroa parasitic mites decreases with increasing humidity (Kraus and Velthuis, 1997). And larvae lose moisture both by respiration and by desiccation owing to the permeability of the larval cuticle (Ellis, 2008). The jelly fed to larvae has a high amount of water which may serve to replenish the water lost.

In contrast to the high humidity levels within the honeycomb cells containing eggs and larvae, bees fan to reduce the humidity in the brood chamber, maintaining it at 40%-60%, (Ellis), 60%-70% (Huang). Besides the humidity from the jelly and nectar fed to the larvae, nurse bee respiration and cuticular loss also introduce moisture to the local environment. It appears that low humidity is not a problem in the brood area. Also, as mentioned in the Temperature section above, bees will cool the brood, if necessary, by distributing water around the brood chamber and evaporating it by fanning.

Above the brood nest in the honey super, nectar is processed into honey by reducing the water in the nectar by evaporation. Bees evaporate the water in nectar by fanning and tongue lashing (see Tongue Lashing Sidebar). To reduce the approximately 50% water content of nectar to the 18% water content of honey, bees must evaporate about one-third of the nectar they forage. (To put this effort into perspective, suppose the bees bring in 3 kg of nectar in a day, then 1 kg of water must be evaporated, a task approximately equivalent to boiling away a quart of water. Picture the energy required for that!) It would appear that low relative humidity, and high vapor pressure deficit in the honey super would enable this energy-intensive process, yet the bees seem to make no effort to control these factors (see Figure 1). Furthermore, there seems to be no research on how beekeepers might optimize the honey super environment for nectar processing.

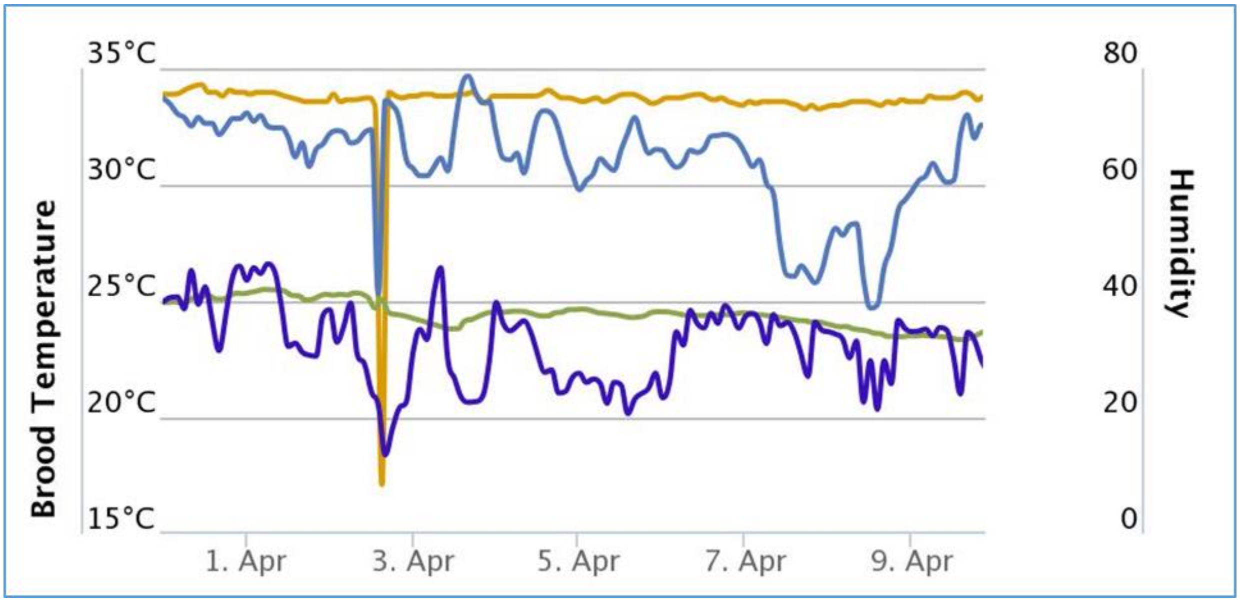

Figure 1. Temperature and Humidity in the Brood Box and the Honey Super. The four lines on this graph show temperature and humidity in the brood box and the honey super in a Langstroth hive near Washington DC in early April 2017. The top two lines are temperatures. The nearly horizontal line shows the bees maintaining the temperature in the brood box at a steady 33ºC. The line just below it is the temperature in the honey super; it is nearly as warm there as in the brood box, but the temperature is not being controlled. The two lower lines record humidity. The smoother upper line shows the bees maintaining the humidity in the brood box between 34% and 40%. The rougher lower line shows humidity in the honey super varying from 15% to 45%. On April 2$^{nd}$, the hive was opened at 3:00 pm and temperature sensors dropped to ambient: 17ºC.

Liquid water is a critical issue for bees in winter. Bees, like all living things, need a continuous supply of water, even in winter, when most water is found in the form of ice or snow. I have seen bees taking up icy water on warmish winter afternoons from the edges of sun-melted snow. Some miscalculate and cool down so much they cannot take flight to return to their hive. It would seem helpful to overwintering bees to have a source of fresh water inside their hive. And, as it turns out, they do.

In fact, they may have too much water. The bees create the water themselves, in the form of vapor, by metabolizing honey. How does this happen? To start with, honey has some water in it. For example, if we assume a super holds 40 pounds of honey, and 18% of it is water, that's 7.2 pounds of water. Then, and more importantly, bees metabolize the sugars in the honey to obtain energy, producing carbon dioxide and water in the process, which bees emit by respiration. Some of that water vapor is removed from the hive by ventilation, the remainder condenses on the cold interior surfaces of the hive. How much water are we talking about? I did the math in a previous article for Bee Culture (Linton, 2015). It turns out that 40 pounds of honey, when metabolized, produces a total of 26.9 pounds of water, over 3 gallons!

Proper ventilation may help ensure that this water plays a positive role in the bees surviving the winter. Just enough ventilation will remove both carbon dioxide and water vapor from the hive. Too much ventilation will require that the bees make an extra effort to warm themselves and may increase their need for water by speeding their desiccation. Too little ventilation will reduce the available oxygen, allow carbon dioxide to build up, and encourage condensation, possibly in undesirable locations.

Depending on the temperature, the condensate may freeze where it forms or drip or dribble to a lower position before freezing. Later, it will melt and continue its downward route. Water on the inner cover may drip down onto the winter cluster, wetting and killing the bees, so having a well-insulated hive top is important. Water on the walls of the hive will run down the sides of the hive and out. You may see it on the mite board.

## What You Could Try

In the tropics some species of honey bee build their nests in the open air where their combs are directly exposed to the weather. In contrast, our bees, *Apis mellifera* build their nests in hollow trees or hives. These have an interior weather (temperature, humidity, and breeze/ventilation) that both the bees and the beekeeper can influence to improve the bees' health and productivity.

Factors under beekeeper control are the number, location, orientation, and size of hive openings, the amount of direct sunlight hitting the hive, the extent of wind protection, the level of insulation on the hive top and sides, and the effect of snow. Hive openings and wind together produce a chimney effect that draws air out of the hive.

Factors that arise from the colony going about its business are warm air from the broodnest and cluster, carbon dioxide and humidity from metabolic processes, and humidity from evaporating nectar and brood rearing.

Colony activities to control the hive environment include fanning – both at openings and within the hive itself, providing and evaporating water, bearding to increase airways, propolizing openings, and possibly, modifying comb structure.

With these things in mind, and considering how the tasks and needs of the bees vary with the seasons, as noted in Table 1, it does not seem farfetched that perceptive beekeepers could, by observing their colonies closely, discern when they were engaging in these environmental control activities and supplement the colony's efforts with actions of their own. Specifically, enlarging or reducing hive openings, exposing or sheltering the hive from sun and wind, and adding or removing insulation.

The second stage for beekeepers, after a few seasons' experience manually optimizing ventilation controls and observing – the assumed – positive effects on their colonies health and productivity would be to automate them. An automated system would have sensors that noticed when the bees were adjusting the hive's internal conditions and would manipulate openings and flaps to minimize their efforts.

An illustrative example of this second stage is Bee Cool Ventilators (http://www.beecoolventilators.com). It is a thermostatically controlled exhaust fan powered by a solar cell. I have no idea whether the product does what it claims; for my taste, there is far too little evidence presented on the website. It is, however, a good example of the concept of a gadget that assists in hive ventilation.

## Avoid Excessive Ventilation

When ventilating hives, whether manually or automatically, one must also be aware of the dangers of providing too much ventilation. Four scenarios come to mind. First, too much airflow through the brood box may result in bees being unable to maintain temperature and humidity within their optimal ranges, thereby reducing the amount of brood the colony can raise. Second, bees communicate with pheromones. Too much airflow may interrupt colony communication by removing pheromones from the hive before they have spread throughout it and had the desired effects. Third, when converting nectar to honey, bees remove a lot of water by the process of evaporation. Both a low relative humidity and a high vapor pressure deficit aid this process, and a warmer hive increases these (Ellis, 2008). Thus, depending on exterior conditions, either increasing airflow or decreasing it may improve the process, it all depends… Fourth, a winter cluster keeps itself warm by consuming honey and vibrating its flight muscles. A proper airflow will remove the products of respiration, including water vapor, which might otherwise condense on the hive ceiling and drip down on the bees, wetting and killing them. Too much ventilation, in contrast, may prevent the bees from breaking cluster to reach their supply of honey and doom them to starvation inches from their stores.

## How to Investigate Ventilation

Earlier we mentioned using sensors to detect when bees were adjusting the hive's ventilation. There are numerous observables that might be monitored, including fanning, bearding, temperature, humidity, carbon dioxide, condensate, airflow, and hive weight change.

To monitor fanning, for example, you might measure the sound of fanning, the heat from the fanners' thoraxes, the presence of fanners at openings, or changes in temperature, airflow, or humidity. To anticipate the need for fanning, the increase in hive weight during a day of nectar flow would be the basis for an estimate of the amount of water to be evaporated from it. Other indicators of a need for fanning include excess temperatures, humidity, or moisture inside the hive. In contrast, direct evidence of too much ventilation when bees are not fanning may be harder to come by. Hypothetically, an active system might reduce ventilation until the bees started fanning, then increase ventilation slightly.

Some tools to monitor fanning are available today, though they may need to be modified for this role. For example, Wyatt Mangum (2017) reported using an infrared camera to detect the heat generated in bees' thoraxes when they were fanning at the hive entrance, as well as to detect temperature differences inside the hive indicating the airflow. Infrared cameras provide new and valuable information to beekeepers, but they require a skilled operator and the images must be captured when no other factors, such as sunlight, affect the temperature of the hive's outer surface. Still, inspired by Mangum's images, one can imagine using a conventional video camera such as Keltronix EyesOnHives, pointed at the hive entrance, together with software to analyze the imagery, to detect fanning effort.

The Arnia colony monitoring system (http://www.arnia.co.uk) measures fanning noise (and flight noise) with a microphone embedded in the unit's electronics box, which is placed just inside the hive entrance.

To monitor hive weight changes, estimate nectar collection, and predict fanning to support evaporation requires a hive scale. There are numerous hive scales are on the market. I have posted a partial list here: http://colonymonitoring.com/cmwp/five-components/sensing/hive-weight.

The examples just given are some of the ways to, potentially, measure fanning, which is just one of the several ways of monitoring ventilation. To summarize, sensors available in today's colony monitoring technologies, that could be used to monitor ventilation processes or activities include:

- Temperature sensors
- Humidity sensors
- Microphones
- Hive scales
- Intelligent video cameras

Sensors that could also be used in beehives include
- $CO_2$ sensors
- Moisture sensors (inside inner cover to measure liquid condensate)
- Airflow sensors (at hive orifices)

Table 1.Potential seasonal indicators of sub-optimal ventilation.

| | | **Respiration** | | **Thermoregulation** | | **Humidity control** | |
|---|---|---|---|---|---|---|---|
| **Internal Situation (HBHC, 2017)** | **Season: Weather assumption** | **Too much ventilation** | **Too little ventilation** | **Too much ventilation** | **Too little ventilation** | **Too much ventilation** | **Too little ventilation** |
| Dormant (broodless clustered, consuming stores) | Winter: Cold, dry, snow | $CO_2$ levels are the same as outside air (0.04%). | $CO_2$ levels are higher than outside air. | Temperatures just outside the brood area, or winter cluster are close to exterior temperature. | N/A | Brood chamber and honey super humidity levels are the same as exterior humidity. | Ice or condensate inside inner cover or on walls of the hive. |
| Population increase (lots of brood, no nectar) | Spring: Warm, rainy, some sunshine | | | | | | Condensate inside inner cover or on walls of the hive. |
| Population peak (lots of brood, lots of nectar) | Summer: Hot, sunny, some rain | | | | Honey super temperatures and brood chamber temperatures just outside of brood area are at, or above, brood temperature, close to exterior temperatures. | | Brood chamber and honey super humidity levels are higher than exterior humidity. |
| Population decrease (little brood, feeding) | Fall: Cool, dry | | | | N/A | | |

## Next Steps

Recall that our goal is to determine what optimal ventilation is, and then to provide it.

Beekeepers, while you are waiting for researchers to determine optimal ventilation parameters and for engineers to provide proven ventilation optimizing gadgets, you can observe your colonies, note their environmental control activities, and supplement their efforts by enlarging or reducing hive openings, exposing or sheltering the hive from sun and wind, and adding or removing insulation. Take care not to over ventilate.

Researchers and citizen scientist beekeepers:

1. Determine what the optimal in-hive environmental conditions are for each major activity, e.g., raising brood, processing nectar, resting, and clustering.
2. Find a means of measuring fanners' energy output, their "horsepower"
3. Put it all together

    a. Determine how much energy a colony of bees expends on ventilation over the course of a typical year in a typical hive.
        i. Besides energy expended, measure colony health and productivity.
    b. Repeat, but with hive modifications that minimize the bees' ventilation efforts.
    c. Compare results.

Engineers and beekeeper gadgeteers:

4. Measure/monitor
    a. Internal and external conditions that stimulate fanning, evaporating, etc.
    b. Air exchange and circulation rates/volumes
    c. Fanners' locations and numbers (and total colony population)
5. Develop hive modifications to minimize fanning, evaporating, etc.
    a. Modify orifice numbers, locations, orientations, and sizes
    b. Modify shading, wind breaks and insulation
    c. Adjust the modifications as needed to minimize fanning, perhaps seasonally, perhaps hourly.

And with that, we will know more and be better beekeepers.

*Frank Linton, Ed.D, retired artificial intelligence engineer, is an EAS-certified Master Beekeeper. Frank hosts the websites* http://colonymonitoring.com, *a guide to colony monitoring technology and* http://thebeepeeker.com, *a guide to observation hives. He is the author of The Observation Hive Handbook, published by the Cornell University Press.*

## Sidebar: Tongue Lashing

**[Begin Sidebar: Tongue Lashing]**

Honey bee tongue lashing dramatically increases evaporation (Louw and Hadley, 1985).

Images of bees tongue lashing nectar are rare. This photo of tongue lashing is the only one I could find on the internet. The photo is by Michael Ellis; the photo and the explanatory caption appeared in an article by Susan Nicolson (2009).

“Female *Allodapula variegata* concentrating the dilute (14%) nectar of *Aloe arborescens* by evaporation. The regurgitated droplet, held under the tongue, is repeatedly sucked in and out and may be very large in relation to the size of the bee (body length 7 mm). Photo, Michael Ellis.”

**[End Sidebar]**

## References

Cook, C.N., Brent, C.S., & Breed, M.D. (2017) Octopamine and tyramine modulate the thermoregulatory fanning response in honey bees (Apis mellifera). J. Exp. Biol. 220: 1925-1930.

Doull K.M. (1976). The effects of different humidities on the hatching of the eggs of honeybees. Apidologie 7:61-66.

Edward E. Southwick & Robin F. A. Moritz. (1987). Social Control of Air Ventilation in Colonies of Honey Bees. J. Insect Physiol. Vol. 33, No. 9, pp. 623-626, Pergamon Journals Ltd

Ellis, M. B. (2008). Homeostasis: Humidity and water relations in honeybee colonies (Apis mellifera). University of Pretoria.

Ellis, M.B., et al. Hygropreference and brood care in the honeybee (Apis mellifera). Journal of Insect Physiology (2008), doi:10.1016/j.jinsphys.2008.08.011

Honey Bee Health Coalition. (2017). Tools for Varroa Management: A Guide to Effective Varroa Sampling & Control. Retrieved 12/31/2017 from: https://honeybeehealthcoalition.org/varroa.

Kraus B, Velthuis HHW (1997). Higher humidity in the honey bee (Apis mellifera L.) brood nest limits reproduction of the parasitic mite Varroa jacobsoni Oud. Naturwissenschaften 84:217-218.

Li Z, Huang ZY, Sharma DB, Xue Y, Wang Z, Ren B (2016) Drone and Worker Brood Microclimates Are Regulated Differentially in Honey Bees, Apis mellifera. PLoS ONE 11(2): e0148740. doi:10.1371/journal.pone.0148740. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4755576/

Linton F. Wait, how much water? There’s more winter water than you thought. Retrieved 12/30/17 from (http://www.beeculture.com/wait-much-water) January 1, 2015.

Louw, G. N., and Hadley, N. F. (1985). Water economy of the honeybee: a stoichiometric accounting. J. Exp. Zool. 235,147 -150

Mandl M, Stabentheiner A, Kovac H (2004) Cooling by water droplets in a breeding honeybee colony. In: Proceedings of the First European Conference of Apidology EurBee (Bernardinelle, I & Milani, N, eds.), Arti Grafiche Friulane SpA, Udine. 59 p.

Mangum, W. A. (2017). Honey Bee Biology. American Bee Journal, November 2017. Pages 1189-1192.

Nicolson, S. W. (2009). Water homeostasis in bees, with the emphasis on sociality. J. of Experimental Biology 2009 212: 429-434; doi: 10.1242/jeb.022343

Sammataro, D., & Avitabile, A. (2011). The Beekeeper's Handbook 4th Edition. Cornell University Press.

Seeley, T. D. (1974). Atmospheric carbon dioxide regulation in honey-bee (Apis mellifera) colonies. J Insect Physiol. Nov;20(11):2301-5.

Seeley, T. D. (2010) Honey Bee Democracy. Princeton University Press.

Stange G., Diesendorf M. (1973). The response of the honeybee antennal CO2-receptors to N2O and Xe. J. Comp. Physiol. 1973;86:139–158.

Sudarsan R, Thompson C, Kevan PG, Eberl HJ. (2012) Flow currents and ventilation in Langstroth beehives due to brood thermoregulation efforts of honeybees. J Theor Biol. 2012 Feb 21;295:168-93. doi: 10.1016/j.jtbi.2011.11.007. Epub 2011 Nov 25.