COLD MUSHROOMS ARE **QUALITY MUSHROOMS**

Postharvest temperature management.

By Dr Jenny Ekman

My old professor at university used to say that the three most important things in postharvest management were Temperature, Temperature and..... Temperature.

Temperature is certainly the key factor determining the storage life of fresh mushrooms. It affects weight loss, colour change, firmness, stipe elongation, cap opening, bacterial growth and overall freshness. While there are many things growers can do to improve quality at harvest (see MushroomLink Summer p11, *Best practice in mushroom supply chains* for more on this), it is the temperatures that mushrooms experience afterwards that are key to determining the quality consumers experience.

WHAT IS TEMPERATURE, ACTUALLY?

Temperature is a measure of the kinetic energy carried by molecules within an object or material. Any collision between a molecule with high kinetic energy, and one with lower kinetic energy, transfers energy from one to the other. To us, this translates as the warmth or coolness of an object or material, whether mushrooms, their packaging, or the air around them.

Unlike mass or volume, temperature (i.e. the kinetic energy of molecules) cannot be measured directly. Rather, we gauge temperature by observing its effects on other materials, such as the expansion of metals, or reflection of infrared radiation.

Einstein said, "*Energy cannot be created or destroyed, it can only be changed from one form into another*".

Heat is one such type of energy.

Respiration by harvested mushrooms converts the energy stored in sugars and carbohydrates into forms that can be used by cells. Some of that energy is also converted into heat. The faster mushrooms are respiring – due to their temperature, development stage or damage – the more heat energy is produced.

For example, using mean respiration rates of mushrooms, it can be calculated that a kg of mushrooms at 19°C produces nearly 21 kJ heat/kg/day. However, respiratory heat drops to 3.5 kJ/kg/day once the mushrooms are cooled to around 5°C (Figure 1). Every degree of cooling decreases respiration, and therefore the heat produced, just a little more.

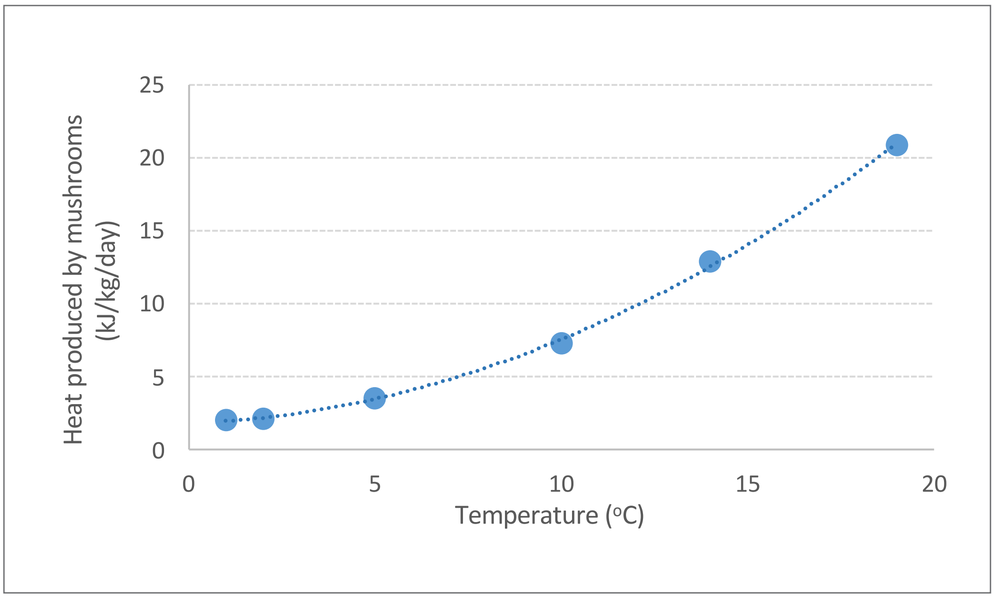

Figure 1. Effect of air temperature on respiratory heat produced by mushrooms. Respiration rates are average values from authors own data. Note this calculation is based on 6 moles CO_2 generating 2,667kJ heat (USDA, 1986), which is not verified for mushrooms.

PRINCIPLES OF COOLING

Cooling is what happens when heat energy is transferred from mushrooms into other media, whether water, air, packaging, or other mushrooms.

As a general rule, the speed at which energy is transferred depends on:

- the medium
- the object's surface area
- the object's thermal conductivity and
- the temperature differential between the object and the cooling medium.

The medium

By the 'medium', we are mainly referring to the air or water that surrounds the mushrooms. However, packaging can also form part of the medium, conducting heat to, or from, the mushrooms.

Air is a poor conductor of heat. Water is a better conductor of heat, transferring energy 24 times as efficiently. If you need proof of this, just think how cold you are likely to get ocean swimming in winter compared to going for a brisk walk. Even though both air and water may be 15°C, that swim is going to be a lot shorter!

Hydro-cooling (immersion in cold water) is clearly not an option for mushrooms. However, just as water can transfer heat away during cooling, it can also allow warming.

A key example is cold room insulation. Like a puffer jacket, cold room insulation works because of the air trapped in layers of foam inside the panelling. This prevents transfer of heat from the outside of the room to the inside.

Older rooms often have poor door and floor seals, or damage where forklifts have punctured the panel skin. If this allows moisture to penetrate the internal foam, the insulation will be ineffective. Likewise, wet, non-insulated concrete floors can allow heat to penetrate the cold room. Poor insulation means increased energy consumption, poor temperature control and lower relative humidity overall.

Surface area

Individual mushrooms have a large surface area relative to their volume. This means they can cool very quickly indeed. However, once mushrooms are packed into a punnet or carton, the effective surface area is reduced to that of the packed product.

If the punnets are placed inside crates on a pallet and the whole load is wrapped with cling film, the effective surface area is only that of the outside of the loaded pallet. The surface area is now low compared to volume, making it hard to remove heat from the mushrooms inside.

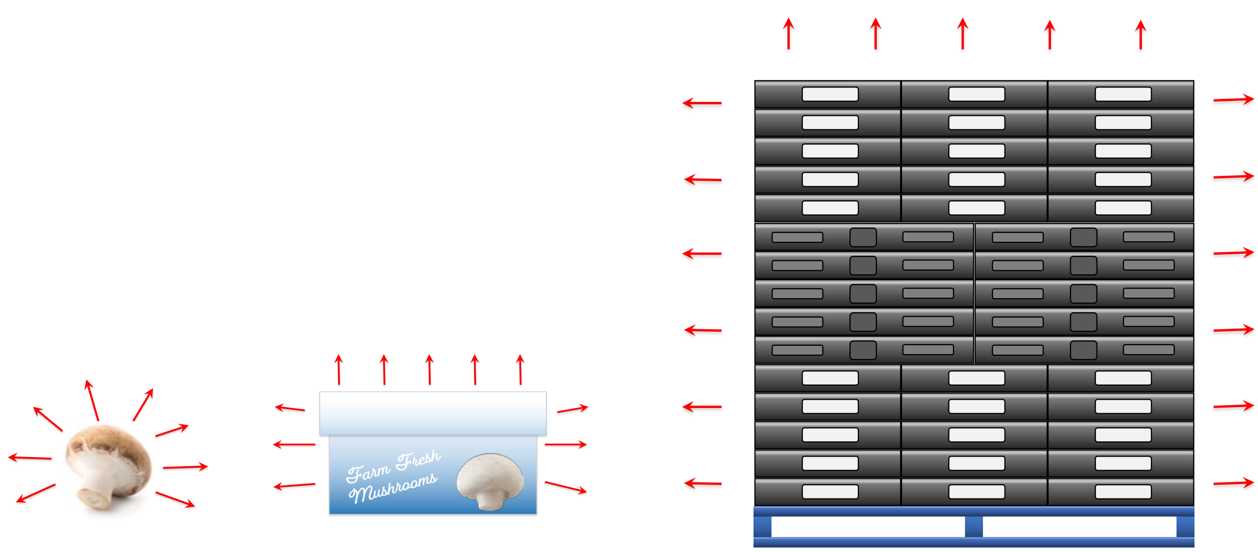

Figure 2. Surface area is a key factor in the speed of cooling. Whereas a single mushroom has a very high surface area compared to its volume, mushrooms inside a carton have only a medium surface area to volume ratio, while stacking onto a pallet reduces surface area to volume even further.

Thermal conductivity

Thermal conductivity is a measure of how easily products lose heat. For example, cabbages are hard to cool because the layers of air trapped in between the leaves prevent heat from moving from the core to the surrounding air.

In contrast, mushrooms have a relatively loose internal structure and lack a true skin. Their thermal conductivity is therefore high, making them easier to cool (Figure 3).

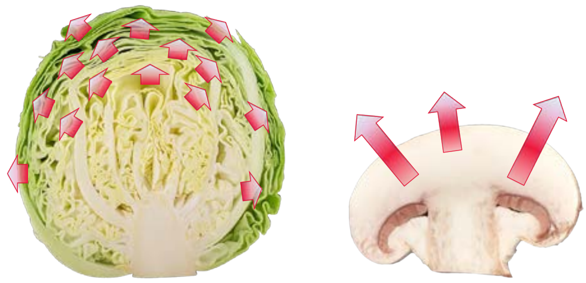

Figure 3. The layers of trapped air between cabbage leaves make it difficult for heat energy to escape. In contrast, the porous structure and lack of a true skin of mushrooms means their thermal conductivity is high, and heat can more easily be removed.

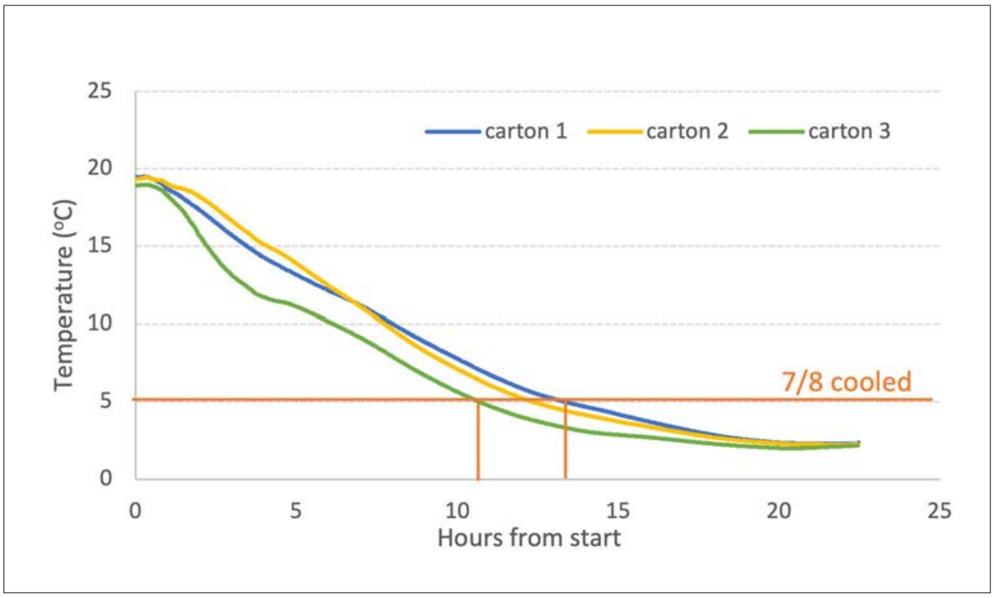

Figure 4. Pulp temperatures inside three cartons of loose mushrooms placed inside a cold room. Temperature fell from 19°C at harvest to a target of 3°C; mushrooms were 7/8 cooled once they reached 5°C, which took 11 to 13 hours.

Temperature differential

Products cool fastest when there is a big difference between them and the cooling medium. As mushrooms approach the temperature of, for example, the cold room air, the cooling rate will slow.

Because the last few degrees take the longest, it is difficult to compare rates of cooling between different systems. It is easier to compare the time taken to '3/4 cooled' or '7/8 cooled'. That is, when 3/4 or 7/8 of the temperature differential between the product and the air has been eliminated.

For example, if the mushrooms are 18°C at harvest, and the temperature target is 2°C, the temperature differential is 16°C.

The mushrooms will be ¾ cooled when they are 6°C and 7/8 cooled when they are 4°C:

$$18°C - (3/4 \times 16°C) = 6°C$$

$$18°C - (7/8 \times 16°C) = 4°C$$

COOLING METHODS

Room cooling

The easiest way of cooling mushrooms is to simply put them into the cold room. However, the cold room air has to remove both their latent heat and the heat generated by respiration, which is faster while mushrooms are warm. This means that cooling can be slow, even when fans are moving air around the room.

If the mushrooms are already packed into cartons or punnets, then cooling will be even slower.

Cooling ratees are important because mushrooms will continue to lose moisture while they are warmer than the cold room air, even if the air is humidified to 85%RH or more.

This is because the warm, moist air spaces inside the mushrooms are essentially 100%RH. This means the air inside the mushrooms can hold a lot more water vapour than the cold room air, even if both are saturated.

Molecules always move from areas of high to low concentrations, and water vapour is no exception. This difference in the partial pressure of water vapour between the warm inner tissues and the cold air effectively pulls moisture out of the mushrooms.

The relationship between the partial pressure of water vapour, temperature and humidity is described by the psychrometric chart. As shown in Figure 5, there is a significant vapour pressure deficit between warm mushrooms and cold room air.

Room cooling is also likely to result in condensation. As warm air cools, it is able to hold less water vapour. The point at which moisture condenses out of the air is the dewpoint. Temperature gradients result in condensation on mushrooms, the inside of packages, and even in different parts of the cold room.

Forced air cooling

Forced air systems pull cold room air through packed product. In effect, this reduces the surface area from the outside of the carton or pallet to that of the mushrooms inside. Forced air cooling rates can be 10 times faster than simply placing the packed mushrooms in the room.

Moreover, as air always moves from cold areas to warmer ones, there is no risk of condensation. Despite the increased volumes of air moving past the product, faster cooling means that weight loss is reduced.

It is important to note that even high amounts of air movement within the room cannot achieve the same effect as forced air cooling. Air is lazy and will take the path of least resistance. Forced air systems **pull** the air

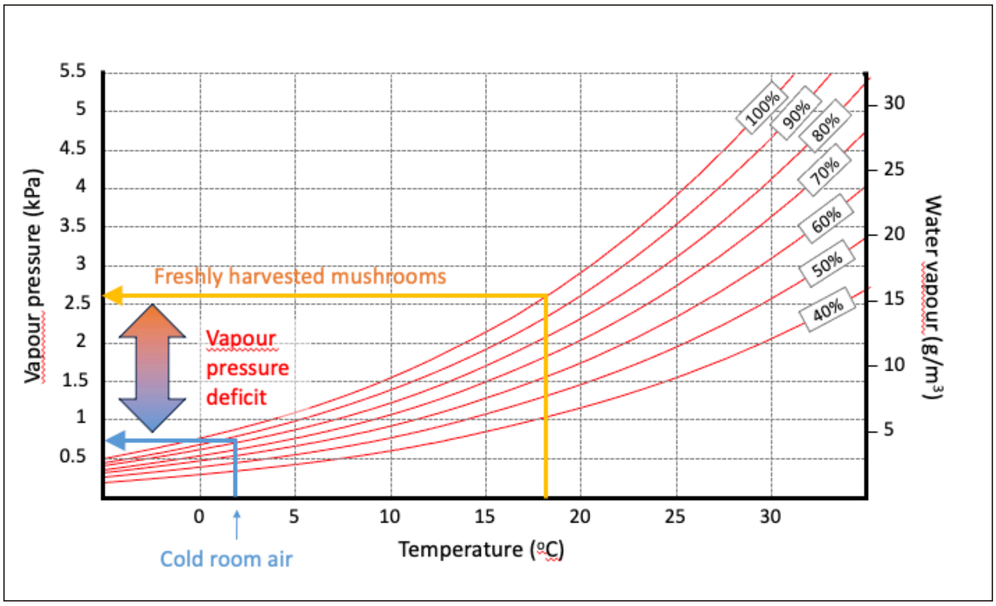

Figure 5. The relationship between temperature, humidity and water vapour pressure is described by the psychrometric chart. In this example, the vapour pressure deficit between mushrooms (18°C + 100%RH) and the room air (3°C + 85% RH) is approximately 1.8 kPa.

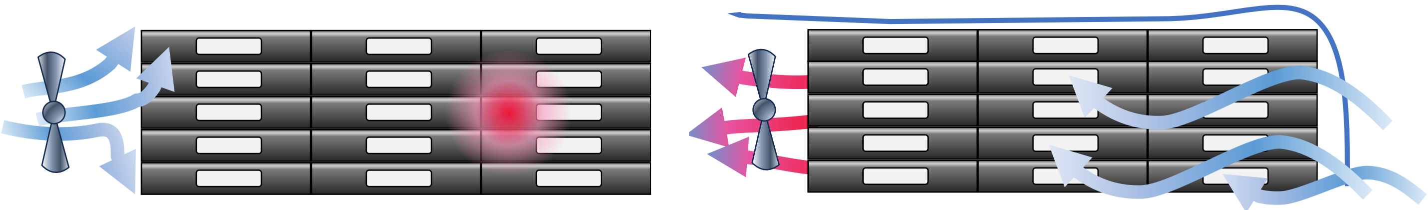

Figure 6. Although blowing air around the cold room can help remove heat from the outside of packed product, warm areas can persist within the consignment (left). Forced air systems pull air through the packed product, cooling product evenly and efficiently while avoiding condensation (right).

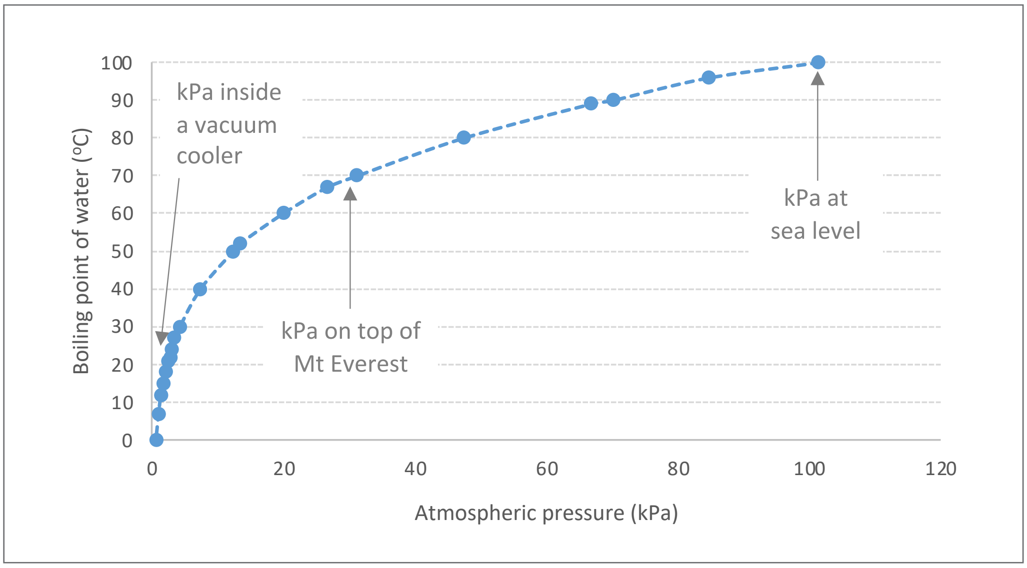

Figure 7. Effect of atmospheric pressure on boiling point of water. Data from myengineeringtools.com.

through the cartons. Fans will simply **blow** it around the outside (Figure 6).

Forced air cooling is widely used for other fresh products. Although rarely used for mushrooms, it does provide a low cost cooling strategy for some growers.

Vacuum cooling

The fastest and most energy efficient way to cool mushrooms is vacuum cooling. Vacuum coolers work by evaporating water from fresh produce. For this reason they work best with products that lose water easily, like leafy greens, herbs – and mushrooms.

At normal atmospheric pressure (around 101.3 kPa) water boils at approximately 100°C. This phase change (liquid into gas) for water absorbs energy. Changing 1ml of liquid water into vapour absorbs 2.26kJ of energy.

This is why water or sweat drying from your face feels cooling in hot dry weather.

As water changes from liquid to gas it not only absorbs energy but also increases volume 1,671 times.

At high pressure the transformation from liquid to gas is more difficult, so more energy needs to be put in to make phase change occur. In effect, water's boiling point increases. Conversely, reducing the pressure means that water changes more easily into vapour.

On top of Mt Everest, reduced atmospheric pressure means that water boils at around 70°C. At 10kPa (1/10th normal atmospheric pressure), water boils at 45°C, while at 1kPa water boils at only 6.7°C (Figure 7).

Commercial vacuum coolers can exert a pressure of close to -100.7kPa, dropping water's boiling point to just

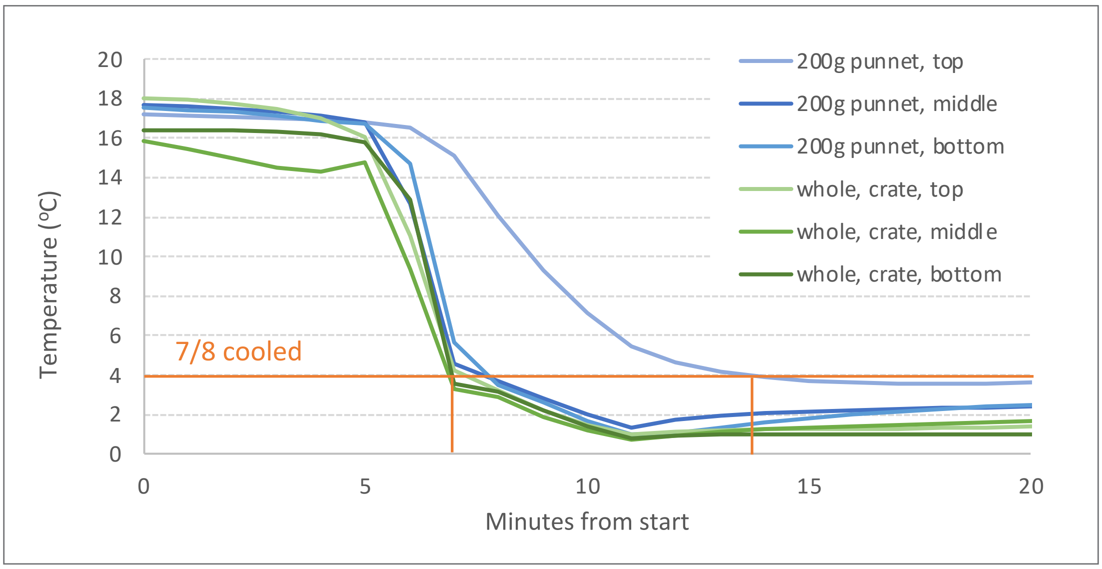

Figure 8. Pulp temperatures during vacuum cooling of packed punnets and loose crates of mushrooms in the top, middle and bottom of pallets. Temperature fell from 17°C at harvest to a target of 2°C; mushrooms were 7/8 cooled once they were 4°C; most reached this in 7 to 8 minutes.

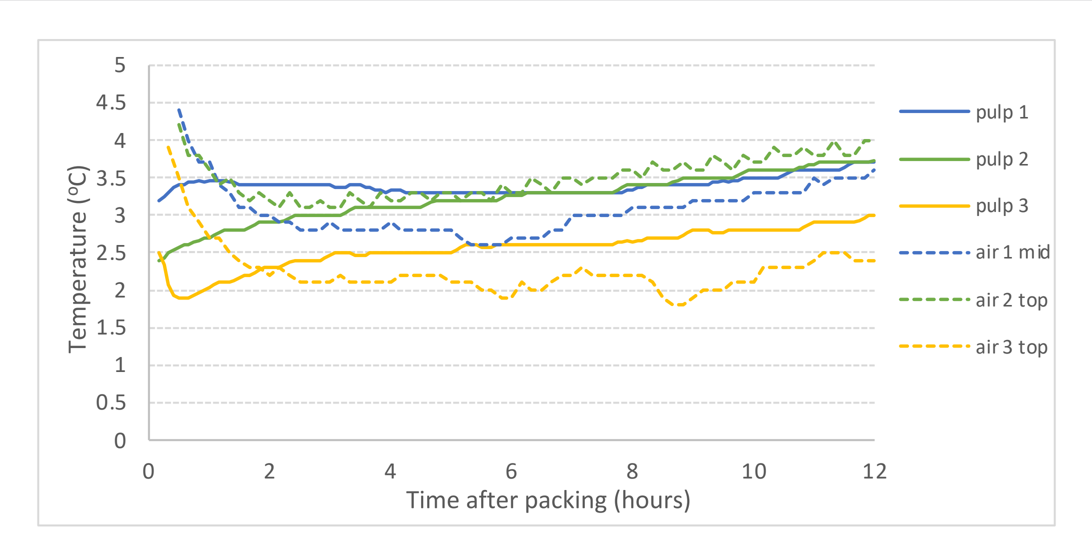

Figure 9. Pulp and air temperatures inside cartons containing sliced mushrooms on three pallets in a single storage room. Cartons were located centrally in the stack (pallet 1) or two from the top (pallets 2 and 3). The cold room was running at approximately 2.2°C.

above zero. It is important to not go any lower as this will freeze the mushrooms.

As cooling is by evaporation, mushrooms inevitably lose some moisture during vacuum cooling; approximately 1% for every 6°C change. However, they can easily lose more weight during room cooling, as the process is much slower.

Unlike other cooling methods, vacuum coolers are unaffected by packaging (as long as water vapour can escape), with cooling fairly uniform through the load.

Vacuum coolers can operate based on a timed cycle or using a probe inserted into the product. The cycle stops once the probe reaches the target temperature. Using a probe prevents 'overcooling', avoiding excess weight loss and energy consumption.

However, if a probe is used, it is essential it is inserted into the largest size mushroom being cooled, with the tip accurately located in the mushroom core.

In this example shown in Figure 8, mushrooms in 200g punnets cooled at the same rate as those in open crates - with a single exception. While 5 of 6 probes reached 7/8 cooled in less than 8 minutes, one took nearly 14 minutes.

The most likely reason for this is that the probe was not fully in contact with the mushroom flesh. Probes measure temperature right at their tip, so if this does not have good contact with the flesh, it will measure air temperature instead. In a vacuum cooler, air temperature falls more slowly than product temperature, so this is not a good measure of cooling.

It is notable that 7/8 cooling was achieved in a few minutes using a vacuum cooler, compared to around 12 hours with room cooling. This difference is likely to have significant impact on quality and shelf life.

ENERGY EFFICIENCY

Cold rooms are good for storing mushrooms, but inefficient at cooling them.

Typically, 5 to 15% of the total load on the cold room is due to transmission of heat through the roof, walls, and floor. If the walls are exposed to direct sunlight this will be much higher. Another 10 to 20% of energy load can be due to internal factors such as people, machinery, lights, fans, and equipment. Depending on how often the door is opened, there may be up to 10% additional load due to warm air infiltration.

This means that only around 55 to 75% of the total energy used by the cold room is actually cooling the mushrooms. If this is not enough to remove the heat energy produced by respiration, the room will be unable to maintain its setpoint, let alone provide cooling.

Using a forced air system dramatically reduces cooling time. Cooling products faster increases the energy efficiency of cooling from 10 to 30% (room cooling) to an estimated 70 to 75%.

However, forced air is still less efficient than vacuum cooling, which is 80 to 85% energy efficient. This is because nearly all of the energy consumed extracts heat from the mushrooms, rather than cooling the air and materials around them.

KEEPING MUSHROOMS COLD

Cooling mushrooms can be thought of as adding value with electricity. Allowing the mushrooms to warm back up cancels that value.

However, this can be harder than it seems, especially once mushrooms are punnetised, packed, and palletised. Their rapid respiration rate can easily increase temperature inside the unventilated punnet.

If heat cannot readily transfer to the surrounding air, then the mushrooms will start to warm up. Higher temperatures mean faster respiration, creating a heat 'snowball'.

In the example shown in Figure 9, pulp temperatures of sliced mushrooms packed into cardboard cartons were warmer than the surrounding air in two of three monitored pallets. Both air and pulp temperatures trended upwards during storage, even though the room remained at 2 to 2.5°C and there was good airflow around the pallets. This demonstrates the difficulty of removing heat from packed mushrooms, especially when inside wrapped pallets.

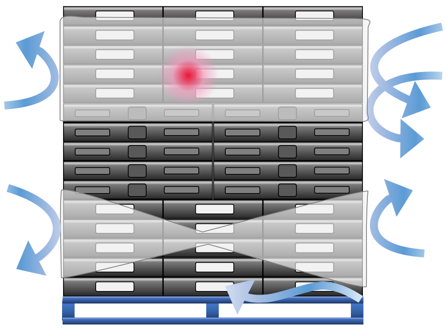

Figure 9. There is little airflow through pallets of packed stock, especially if they have been plastic wrapped to stabilise the load. Without airflow, heat energy produced by the mushrooms cannot be removed, potentially allowing hot spots to develop.

MANAGE THE RISK OF WARMING

Techniques to help reduce risk include:

- Handle mushrooms gently, especially sliced product, as damage increases respiration rate
- Cool mushrooms thoroughly, preferably using vacuum cooling
- Don't wrap pallets until despatch, so as to allow air movement through the crates / cartons
- Maintain air flow around pallets
- keep them well spaced inside the cold room
- leave a gap of at least 20cm between pallets and the walls
- Add a fan to circulate air around the room
- Check the room insulation, making sure it is sealed against moisture
- Minimise door opening and consider adding air curtains or airlocks to reduce ingress of warm external air
- Ensure the room cooling capacity is sufficient to remove the heat generated by respiration at peak loading

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Hort Innovation MUSHROOM FUND

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Key points

- Temperature is a measure of the kinetic energy carried by molecules.
- Temperature is the primary factor affecting mushroom storage life and quality, influencing weight, colour, firmness, and bacterial growth.
- Mushroom respiration generates heat, with higher temperatures increasing respiration rates and, therefore, heat.
- Cooling rate depends on the cooling medium, product surface area, thermal conductivity, and temperature differential.
- Room cooling, forced air, and vacuum cooling are common cooling methods, with vacuum cooling being the fastest and most energy efficient.
- Room cooling is slow and likely to result in condensation, reducing mushroom quality and storage life.
- Once mushrooms are cold, preventing re-warming is crucial for maintaining quality.
- Strategies to limit re-warming include thorough pre-cooling, maintaining airflow through and around pallets, reducing ingress of warm air and ensuring the cold room is operating efficiently.