On Cooling Boxes and Pallets

I would like to discuss a problem associated with heat transfer that I’ve encountered a number of times: the cooling of pallets. Because of the pressure to minimize capital expenditures, we are sometimes tempted to pack warm product in cases, palletize the cases, and send the warm pallet and cases to a warehouse for cooling or freezing. The decision to do this is often done without a complete understanding of the consequences of this action.

How does this happen? Sometimes, when dealing with a new product, there is only a limited availability of material to perform tests on. Perhaps only a single case of material is available for testing. During the course of setting up a production line, the costs become a concern and someone questions the need for a cooler for individual products or cases. A simple test is run to try to find out whether or not the product can be cooled as a pallet.

The holder of the single case of product inserts some thermocouples into the case and puts the case into a walk-in cooler or a cooled warehouse. They find that it takes about a day or less to cool. For the purposes of discussion let’s assume that the case is a 30 × 30 × 30 cm cube. Furthermore, as a first approximation, assume that a pallet of these cases is 4 cases × 4 cases × 4 cases, or about a 120 × 120 × 120 cm cube. The experimenter, not being an expert in heat transfer problems, says, “If a box that’s 30 cm on a side takes about a day to cool, then a cube (the pallet of cases) that is four times larger should take about four days to cool.” With this four day estimation in hand, the experimenter then makes a decision about whether or not taking four days to cool down the product will adversely affect the product’s quality. Let’s assume that the experimenter concludes that four days to cool the product is acceptable. He/she reports, “It looks okay to design the operation to cool pallets.” The decision, which I will now show to be erroneous, has been made.

To illustrate the unreality of the assumption that a pallet will take about four times the time required to cool a case, I undertook a simple model calculation. I assumed that the content of the case was going to be cooled from 50°C to 25°C in a 20°C environment. I further assumed that the contents of the case had the properties of water at about 35°C.

To estimate what the rate of heat transfer was between the surrounding air, I chose a value of 4.4 watts/sq.m.-K for the heat transfer coefficient, which is what one would get with air that is barely moving. I found the thermal conductivity of corrugated cardboard in the literature (about 0.052 watts/m-K, which is a pretty good insulator), and I assumed that the cardboard had a thickness of 3.2 mm (about 1/8 of an inch). I then used information readily available in the literature to calculate how long this cooling process would take.

This is a basic problem in heat conduction. The method for doing this calculation may be found in any standard textbook that discusses heat transfer. I followed the procedures described in Heldman and Singh (1). This section uses the simple, approximate “j” and “I” factors, rather than the more difficult to use methods found in classical heat transfer engineering texts. The only thing that is not described in this text that one needs to know is that the effective external heat transfer coefficient is the reciprocal of the sum of the resistance due to the convective heat transfer and the resistance of the cardboard. Other than that undescribed factor, the calculation procedure is completely laid out for the reader.

The calculation takes only a couple of minutes. One finds, for my idealized scenario, that the time required to cool the center of the case from 50°C to 25°C in a 20°C environment is about 47 hours, or just under 2 days.

I then repeated the calculation, assuming the pallet was a giant single case, 120 cm on a side, being exposed to the same environment, and having the same thickness cardboard as the single case. This, as will be discussed, is obviously not realistic. For this unrealistic condition, the calculation was repeated. The calculated time was about 376 hours, or nearly 16 days! Note the that the pallet doesn’t take four times as long to cool as our hapless experimenter assumed, but actually takes about eight times as long.

In fact, the problem is even worse than this, and impossible to solve mathematically. If you draw a sketch of the stack of cartons, you will see that the problem is much more complicated than I’ve assumed. As one passes through the pallet, one encounters a single thickness of cardboard, then the contents of a case, then a double thickness of cardboard and the contents of the case three times, followed by a single thickness of cardboard. In other words, the resistance to conduction is much larger than I assumed in my giant case example. The heat traveling to each side of the pallet has to pass through four insulating layers of cardboard as it travels from the center, not the single layer that I assumed. To approximate this situation, I made my giant case have a thickness of cardboard four times that of an actual case. The calculated time required to cool is now about 465 hours, or over 19 days! This is about 10 times the time required to cool a single case.

Once again though, the problem is even worse than I described. As heat travels from case to case, it encounters significant additional thermal resistance because the cases are not in perfect thermal contact with one another (There is a tiny layer of air between them). It’s difficult to find data on this type of resistance, which is called a contact resistance. I found one reference that indicates that two layers of this resistance, which is the number of
times the heat has to pass through this resistance on its way out from the center of the pallet, is about the same magnitude as the resistance that is created by the four layers of cardboard. When this amount of resistance is added to the calculation, the time required to cool the pallet is about 560 hours, or over 23 days! This is about 12 times the time required to cool a single case.

It’s not difficult to show that, for cooling a homogeneous mass of material, the time required approaches the square of the characteristic dimension. Or, in the limit, one would expect that in this case, the pallet could take as much as 16 times the time required to cool the single case. It is this factor that I usually use as a first approximation. The reader should be able to see that we are approaching this limit. The reader should use this approximation before even agreeing to run the experiment on a single case.

If a similar calculation were done for freezing, one would reach a similar conclusion. That’s why it’s not a good idea to freeze unstable products when they are in a pallet. The freezing time becomes so long that one may obtain excessive ice crystal growth, or in the case of labile components, such as vegetable materials, one may observe significant oxidation of components.

I hope reading this column will protect the reader from blindly making a potentially disastrous mistake in the future.

Reference


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