Atmospheric freeze-drying – an enabling technology

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The project team, from left, Dr. Qun Chen, Prof. Jim Jones, Prof. Richard Archer

Introduction

Drying is one of the most important techniques for food preservation. But it takes time, costs money and may rob the product of some colour, flavour or nutrient. Drying is always a compromise and not all products demand the same outcome. Chewy or crunchy, tough or brittle, fresh, cooked or smoky may be desirable in different products.

Hot air drying is simple, low-cost and ancient. It is fast and effective, but may damage heat-sensitive compounds. Heat pumps can make the operation closed cycle, cooler and drier. But heat pumps are more expensive and shift the energy demand from heat to electricity.

In vacuum freeze drying (VFD) deeply frozen food is slowly heated to sublimate ice from the food products inside a vacuum chamber. A condenser, at about -40°C, traps the water vapour as ice or frost. Drying rate is a balance between getting heat into the product and removing the water vapour by diffusion though the drying food matrix. The water vapour is then condensed as ice in the condenser. This continues until all the ice is all sublimed, after which the cooling effect of sublimation disappears and the heat inflow warms the food material.

VFD gives high quality but is expensive compared to hot air. New Zealand has several successful freeze-drying companies, mostly using batch units. Continuous VFD is generally expensive and rare.

However, freeze-drying can be performed using a carrier gas, perhaps using very cold air, at atmospheric pressure rather than under a vacuum. This is atmospheric freeze-drying (AFD). It uses the water vapour pressure gradient to drive drying, which is very small at cold conditions in air, due to the low equilibrium water vapour pressure. Thus, AFD requires a large volume of air (or other carrier gas) and long times. This project tested the proposition that using desiccants and a smaller (than for VFD) refrigeration plant could offer an economic and effective system for New Zealand. We would expect product close to VFD quality for a cost closer to hot air drying.

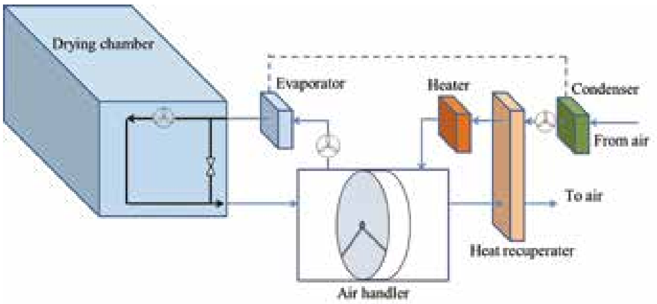


Figure 1: Desiccant wheel AFD with heat pump regeneration

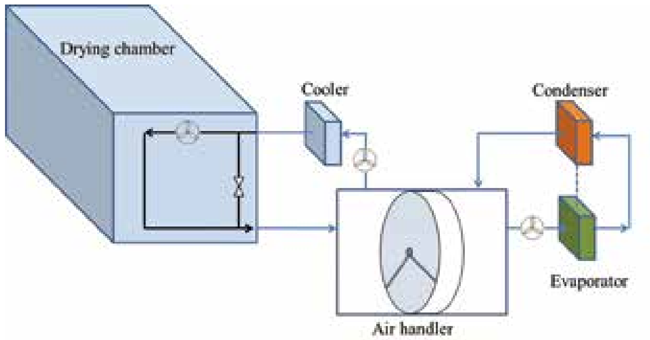


Figure 2: Desiccant wheel AFD with open air regeneration

Scope of research

A small research team from Massey University (MU) and Plant & Food Research (PFR) is applying desiccant wheel dehumidification to atmospheric freeze-drying of New Zealand foods. We aim to use standard desiccant wheels to maintain a light-weight, insulated chamber at a set temperature and dew point and to dry product in that chamber. We have developed models for mass and energy flows in the coupled dryer and air handling unit and are optimising the process configuration for simplicity and low energy costs. We are building a prototype for test drying real New Zealand food materials.

Meanwhile, the team also aims to understand the behaviour of food material during drying. We will investigate the mechanisms controlling drying rate and develop a standardised method for determining the ideal temperature trajectory for various products.

Atmospheric freeze-drying

In atmospheric freeze-drying, ice sublimation happens under atmospheric pressure provided the drying air is not saturated with water vapour. Diffusion of water vapour through porous food is controlled primarily by the partial pressure gradient of water vapour independent of the absolute pressure in the system. Heat required for sublimation is transported to the ice front by both drying medium convection to the object surface and heat conduction through the dry layer. The drying rate is dominated by the resistances of heat transfer and water vapour mass diffusion through the dry layer. The ability of heat to be carried by air to the product may speed the process relative to VFD but diffusion of water molecules through a medium of air molecules will slow it.

An atmospheric freeze-dryer consists mainly of a drying chamber and an air handler unit to dehumidify the gaseous drying medium. Frozen food is dried on trays, belts, or in a fluidised bed similar to convective hot air drying. The dehumidification system is used to remove water vapour from the gaseous drying medium that carries moisture out of the drying chamber and to control the temperature of the drying medium. During the past few decades, NTNU and SINTEF in Norway have been developing an atmospheric freeze-drying process with a heat pump for dehumidification. However, over 80% of the heat removed by the evaporator coils of the heat pump (where the water vapour is condensed as ice or frost) is contributed by the sensible heat from air cooling. This all demands electricity to drive the heat pump compressor. Moreover, drying is interrupted when the evaporator coils are defrosted.

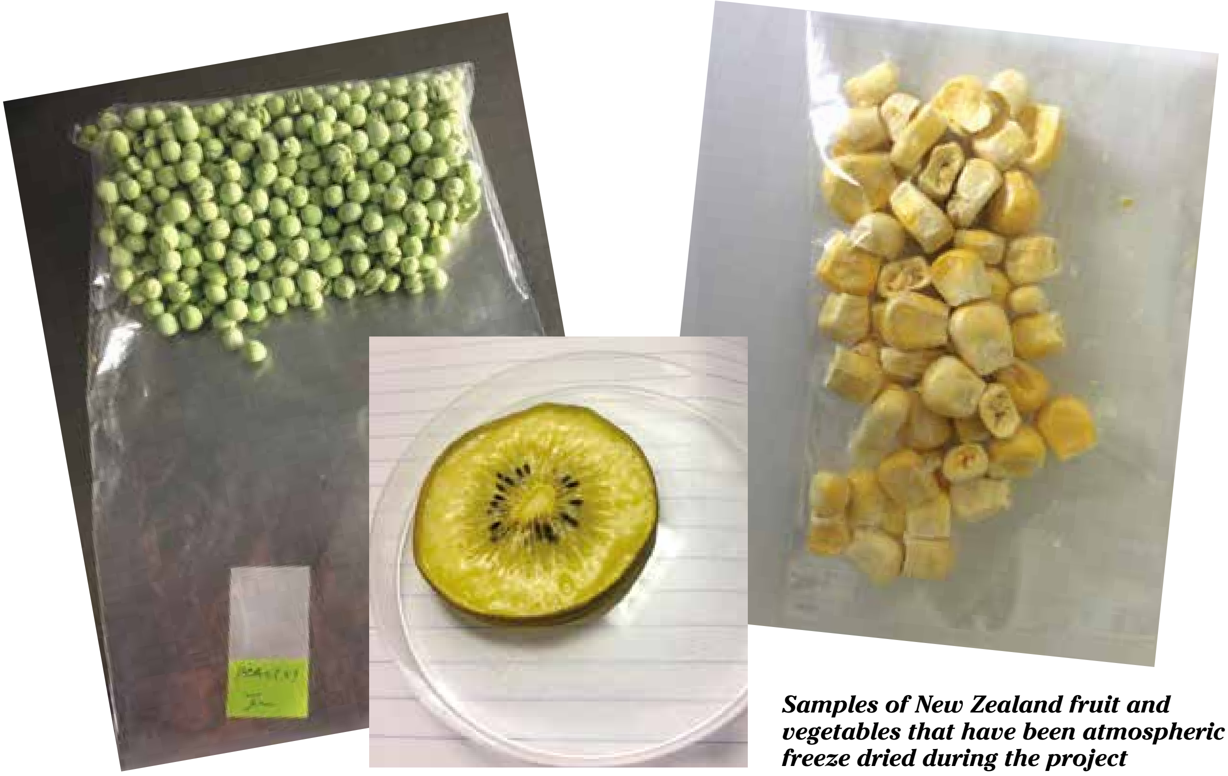
Dessicant wheels

Alternatively, modern desiccant dehumidification uses desiccant wheels to remove moisture without lowering temperature. Desiccant wheels are now widely used in HVAC applications including at freezer temperatures.

In a desiccant wheel AFD, the moist drying gas exiting the drying chamber is continuously dehumidified by passing it through one section of the desiccant wheel in an air handler, which then recirculates it back to the drying chamber. In addition to the desiccant wheel, this air handler circuit includes a heat pump (Figure 1) or a heater and recuperator (Figure 2). In a second circuit, hot air is contacted with a second part of the desiccant wheel, which removes the moisture. Because water vapour is much more soluble in hot air, this is an effective way to concentrate the moisture from low temperature drying gas into a smaller flow of high temperature regenerant gas.

In one form of our AFD (Figure 1), the regeneration gas stream is itself dehumidified by the evaporator coil of a heat pump and then recirculated to the desiccant wheel via reheating at the condenser of the heat pump. This forms a closed loop and allows the drying and dehumidification to operate with non-air atmospheres, perhaps oxygen-depleted, which are especially suitable for food products with oxygen sensitive nutrients. In this case, only electricity is needed for the whole drying process.

In both cases, however, the energy cost for operating the atmospheric freeze-drying process looks to be about 50% of a vacuum freeze-dryer. The trade-off is with time – AFD is slow. Some products may take a



Samples of New Zealand fruit and vegetables that have been atmospheric freeze dried during the project

week or two to dry. For a large scale application this merely demands a larger freezer room as the chamber. AFD looks to be better suited to large-scale semi-continuous drying, unlike the small batch drying that VFD is best suited to.

Applications

In the drying process under development, food material is dried on trays stacked on trolleys moving semi-continuously in the drying chamber under atmospheric pressure. As a result, the process can dry food material without size limitation, as long as it can fit on trays. The chamber is not a vacuum chamber, and hence can be constructed with low cost. Should the drying rate be a tenth that of VFD and the chamber needs to be 10 times larger than the equivalent VFD, the investment cost for the atmospheric freeze drying process could be about 60% of that of the vacuum freeze-dryer of the same capacity.

Atmospheric freeze drying can be used either as standalone drying units or for pre-drying before a vacuum freeze-dryer allowing a less expensive capacity doubling for the existing freeze-dryer. The combination makes best use of AFD and allows an efficient debottlenecking of an existing VFD unit.

The drying medium flows counter-current to food material through the chamber. The drying medium not only provides heat for ice sublimation but also carries moisture out of the drying chamber. The temperature of the drying medium could range from -10°C (as freeze-drying) to above the triple point (as chill-drying) as demanded by the material being dried. In AFD the product will never climb above the chamber inlet temperature, unlike VFD where product can warm up to shelf temperature towards the end of the drying process.

In AFD, the drying temperature is a compromise between the freezing point of food materials and the temperature-dependent water vapour holding capacity of the drying medium. As a viable trade-off between quality and drying rates, the freeze-drying temperature should be above -10°C. This suits AFD best when drying food with low sugar or salt content.

The new process is also suited to drying at chill temperature up to 10°C (or any temperature judged safe). This process can thus substitute hot air drying in order to improve the dried product quality.

Similar to VFD, atmospheric freeze-drying can dry products to higher qualities than those obtained with convective hot air drying methods. The dried products retain the vast majority of nutrients with high structural rigidity, high rehydration capacity. In tests so far, the colour, taste and texture of rehydrated products are very similar to the original products. AFD offers the opportunity to add these high-quality, flavoursome dried fruits and vegetables to a range of different foods such as healthy snacks or inclusions in a wide range of products. By contrast, hops dried with AFD may offer opportunities for an even wider range of craft beers with unique NZ hop flavours. The possibilities for new uses of these ingredients or new products are still to be further explored.

As a horticultural nation and exporter of high-quality food, New Zealand needs to dry fruit, vegetables, glands, mussels, hops and other fresh or frozen food materials. By 2015, the annual exports of dried fruit and vegetables reached a modest NZ$11.8m and are climbing. AFD may enable affordable freeze-drying of new materials and so add value to dried fruit and vegetable exports.

FIET
Food Industry Enabling Technologies

Food Industry Enabling Technologies (FIET) is funded by the Ministry for Business, Innovation and Employment and its purpose is to support new process developments that have the potential to add significant value to our national economy. The programme has six partners, Massey University (the host), Riddet Institute, University of Auckland, University of Otago, Plant and Food and AgResearch. Funding is $18m over six years (2015-2021) and targets pre-commercialisation activities. If you are interested in more information, then please contact either Dr Jo Kerslake, FIET Programme Director, (j.i.kerslake@massey.ac.nz) or Professor Richard Archer, Chief Technologist, (R.H.Archer@massey.ac.nz).