LOW TEMPERATURE DRYING WITH HEAT PUMPS NEW GENERATIONS OF HIGH QUALITY DRIED PRODUCTS

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Abstract

Heat pump dryers have found their application in drying of heat sensitive materials due to the possibilities of controlling drying conditions. In addition, this technology is energy saving and more environmentally friendly than direct heated dryers. In Norway, research on this technology has taken place over a period of 20 years and several industrial applications are seen, like drying of fish and vegetables. Several products have been dried in test plants, like fish products, fruits, vegetables, dairy products, biological active products and other heat sensitive materials. For such products quality can be controlled, like color, taste, bulk density and rehydration properties.

In this paper design, energy consumption, operation modes and criteria and influence of product quality of heat pump dryers are presented. The interaction between the drying chamber and the heat pump operation are studied. Heat pump systems with different environmentally friendly working fluids are simulated. Simulations are done at different drying conditions and at different evaporating temperatures. Consequences on the dryer thermal efficiency and the heat pump coefficient of performance are studied at different operational modes.

Quality aspects and energy consumption at different operational modes in drying of different food products and chemical pulp are studied. Drying at 20^{o}C with initial freeze drying have shown a considerable increase in water retention value and in the tensile index.

1 Principles of heat pump drying

A schematic layout of an adiabatic heat pump fluidized bed is shown in Figure 1.
The advantages of the heat pump dryers are

- low energy consumption due to a high SMER that is expressed by:

$$SMER = COP/(dh/dx) \quad (1)$$

$$COP = Qo/W \quad (2)$$

Typical SMER are in the order of 2 to 5 (kg water per kWh) depending on the drying temperature.

- Drying conditions can be regulated with drying temperatures from –20°C to +110°C. Quality parameters of the product can be controlled due to the low temperatures and the possibility for partly freeze drying.
- The technology is environmentally friendly due to the recirculation of the drying air and the high thermal efficiency of the dryer.

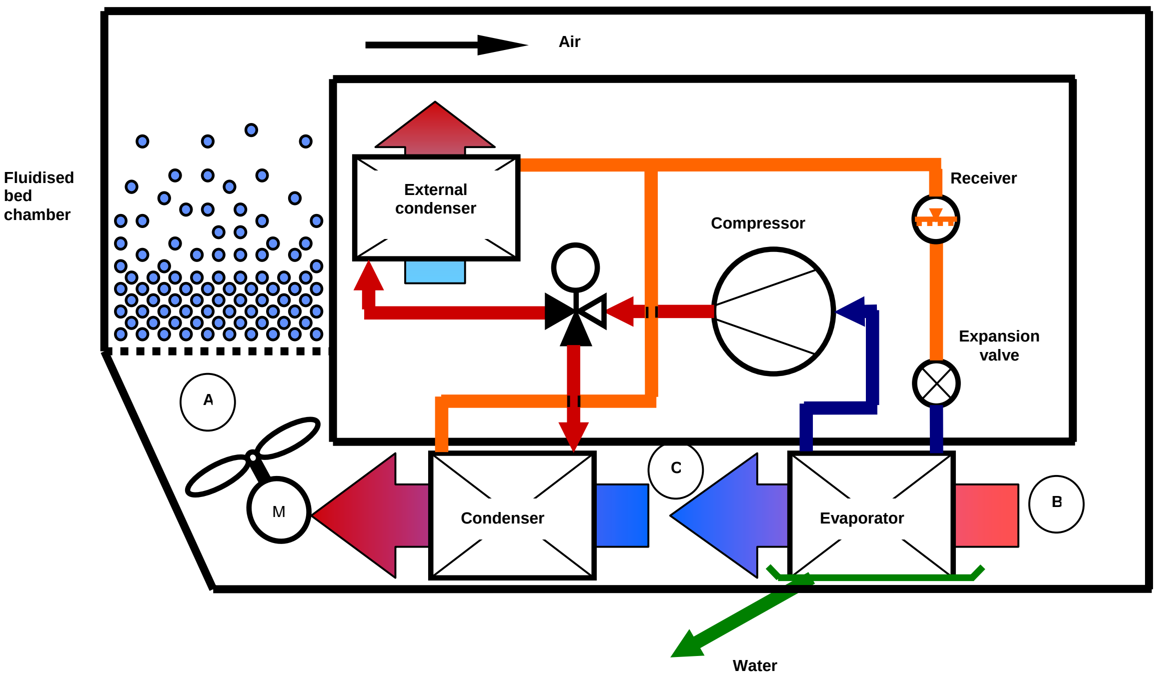

Figure 1. Schematic layout of a heat pump fluidized bed dryer

In fig. 2 the process is shown in the Mollier diagram for humid air. Depending on the design, dimensioning and the drying kinetics of the product there might be an optimum design point with respect to the SMER-ratio given by dh_{opt} in the diagram. At this point SMER has its highest value [Eikevik 1999], [Strømmen 1999].

2 Working fluids in heat pump dryers

A heat pump dryer are normally operated in a subcritical cycle with respect to the working fluid in the heat pump. The newest development at NTNU/SINTEF in Trondheim, Norway is a heat pump dryer with CO_2 as the working fluid operated in a transcritical cycle . In this case the SMER can be improved in the intermediate temperature (30°C to 50°C) drying range compared to subcritical operated heat pumps. Theoretically, in a CO_2 transcritical operated heat pump dryer, the SMER can be in the order of 20-30% higher compared to subcritical heat pumps when the inlet air drying temperature is 30°C to 50°C. See figure 2 and 3.

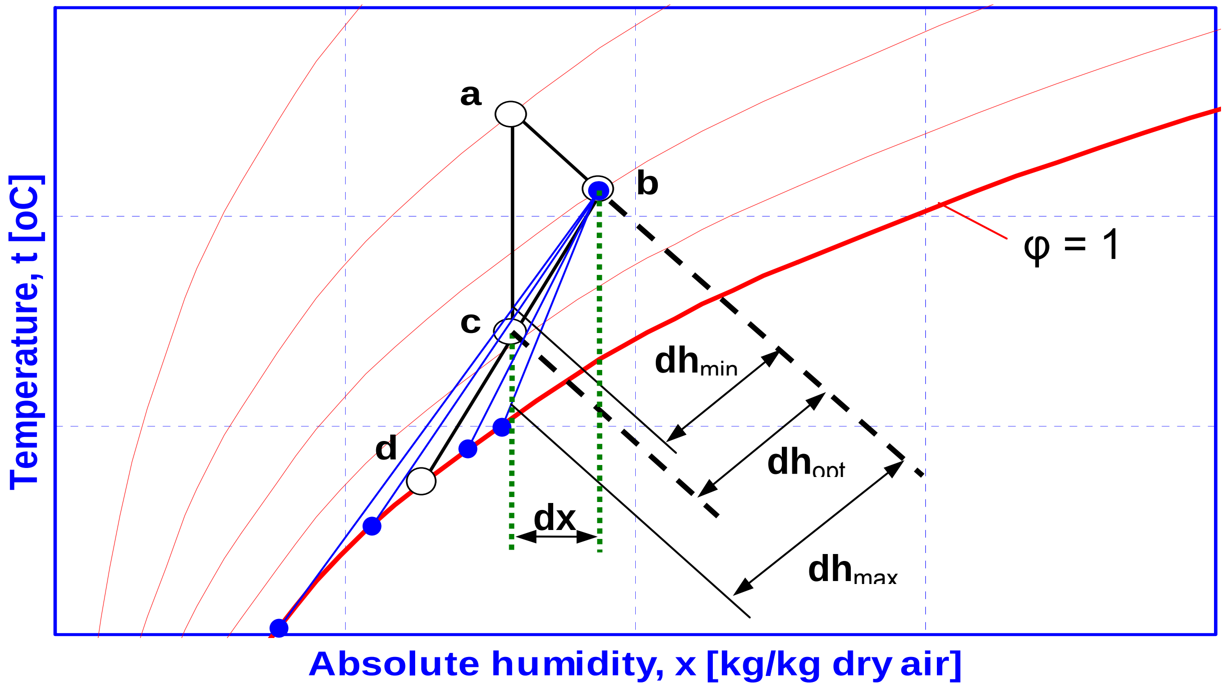

Figure 2. Mollier chart for humid air with heat pump drying process state points

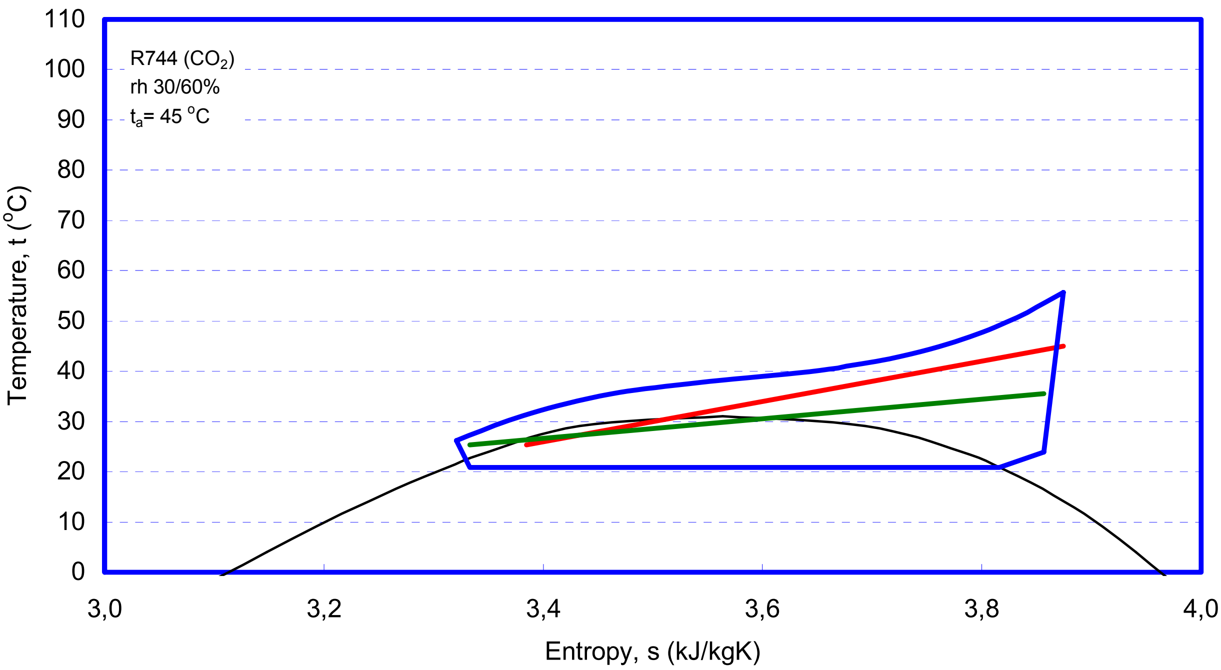

Figure 3. Temperature-entropy diagram for the heat pump dryer with carbon dioxide in transcritical cycle

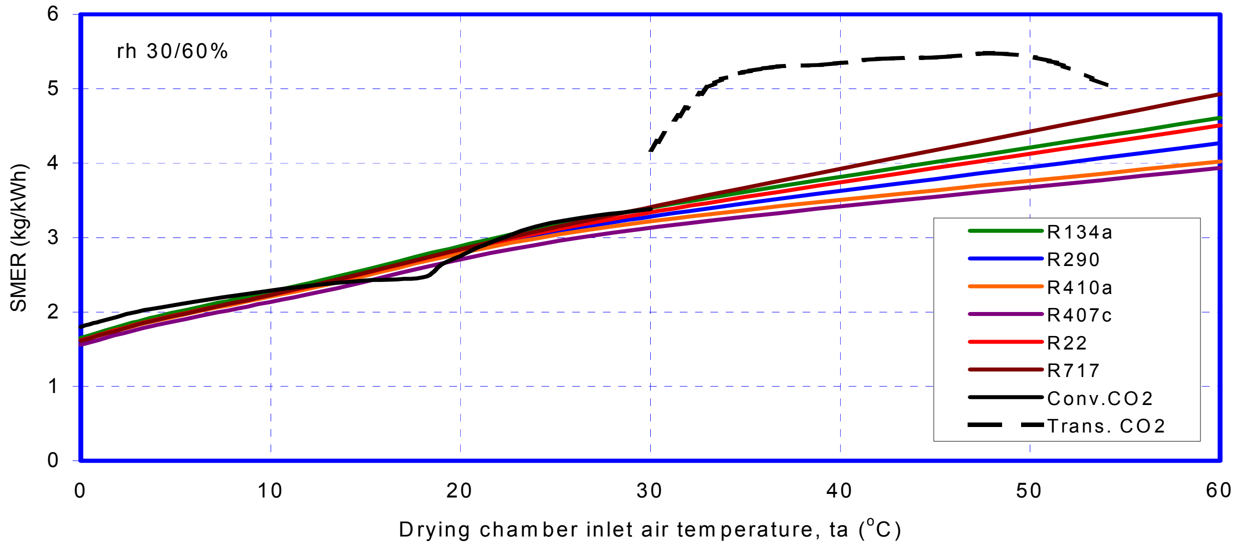

Figure 4. SMER as function of air temperature for different working fluids and CO_2 at conventional and trancritical cycles

3 Properties and quality of low temperature heat pump dried products

3.1 Drying of cod pieces with initial atmospheric freeze drying

Quality parameters of the dried products are influenced to a large extent by the drying temperature. Figure 5 shows the influence on bulk density for 5 mm cubes of cod fish dried at different temperature from –10°C to 30°C. The final water content was in all cases below 10 % and initial water content about 80 % wet basis. In some of the drying tests a temperature program was used with varying time period at drying temperatures below the freezing point of the product. As can be seen from figure 5, the lower the drying temperature and the longer time period with freeze drying temperatures the lower the bulk density of the cod pieces. This again will influence the rehydration ability of the product [Strømmen 1985????]

Longer time with initial freeze drying gives higher rehydration ability. For cubes of codfish given in figure 5 dried in 10 hours at –5°C the cubes are rehydrated after 30 seconds in water [].

Several food products are dried at operational modes with initial freeze drying, for instance leek, corn and peas. All these products show considerable quality improvements with such an initial freeze drying step []

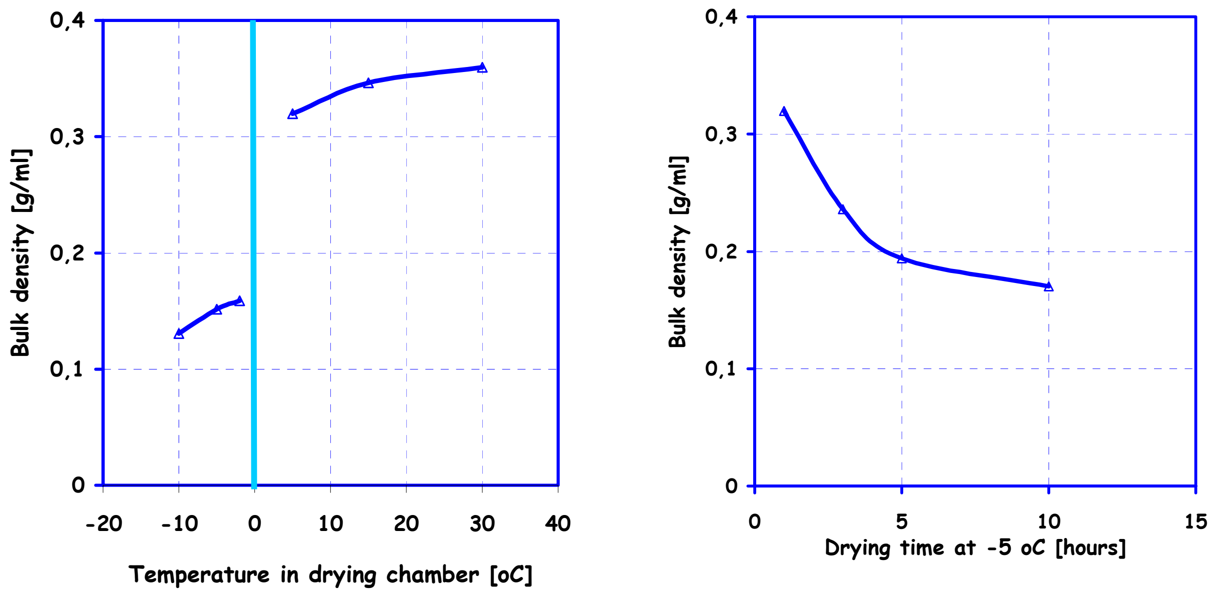

Figure 5. Bulk density of cod pieces dried at temperatures from –10°C to 30°C

3.2 Drying of chemical pulp at low temperatures

Heat pump drying has also been tried for drying of chemical pulp. The concept is based on drying in combinations with heat pump. This makes it possible to dry at low and moderate temperatures and ability to optimize product quality. Initial drying experiments have shown that better quality is obtained by this drying method. The drying temperature was chosen to be –15°C (below freezing point for the pulp) and +20°C. Examples of such quality parameters are swelling, which can be assessed by water retention value (WRV) and tensile index respectively. Water retention value (WRV) is a measure of the fibres ability to swell. It is an empirical measure of a sample of pulp fibres ability to retain water. The WRV value increases with increased beating due to internal and external fibrillation and delamination of the fibre wall. The WRV (g/g) gives the amount of water that is present in the pulp after centrifugation with a certain centrifugal force (3000 ± 50 g) a definite period of time (15 minutes). The swelling is often assessed by plot of a beating curve, where WRV is measured as a function of the degree of beating, given as evolutions in a PFI mill (A PFI mill is a standardized laboratory mill, used to assess effects of milling by the pulp and paper industry world wide). Tensile strength is the maximum tensile force per unit width that paper and board will withstand before breaking under the conditions defined in the standard test method. Tensile index is tensile strength divided by grammage (which is g/m^2). A test piece of given dimensions (width 15 mm ± 0.1mm, test length 180 ± 1 mm) is stretched to rupture at a constant rate of elongation using a tensile-testing apparatus that measure the tensile force. The tensile index is used to quantify the strength of a paper. The weak link in paper is not the fibre itself, but the bonds between the fibres. Thus, the tensile index is a measure of the joint strength of fibre – fibre bonding.

Figure 6 and 7 shows the water retention value and the tensile index as a function of revolutions in a PFI-mill. The undried pulp have the highest value in all cases, and represent the reference quality. The mill dried pulp has the lowest values. The differences between those two represent the quality loss with the present drying technology. The curves in between represents the new drying technology dried at two different temperatures (not optimized). Both water retention value and tensile index is increased substantially compared to drying with the present technology. Water retention value is improved by 20-30 % and tensile index with 7-10 %.

A potential for large energy savings is revealed. In the traditional drying process the SMER is 1,3 (kg water removed per kWh). The new drying concept with drying at +20°C will increase the SMER to 3,2. For a chemical pulp mill with annually pulp production of 400.000 ton this gives the following figures:

Current drying process:	310 GWh/year
New drying process:	130 GWh/year
Energy savings:	180 GWh/year

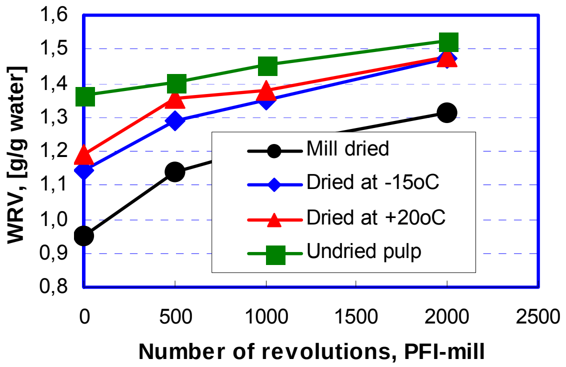

Figure 6. Water retention value as a function of revolutions in a PFI-mill

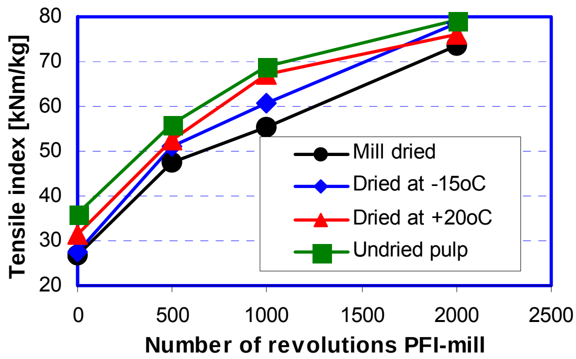

Figure 7. Tensile index as a function of revolutions in a PFI-mill

In this case the highest WRV and Tensile index are achieved at 20°C drying temperature and not a combined mode drying. However the process is not optimized. Further research will study the mechanisms of the improved water retention value and tensile index when the chemical pulp is dried at low temperatures. [Lauritzen, 2003]

4 Energy consumption in a heat pump dryer operated at a combined mode drying

To achieve as high SMER as possible, industrial fluidized bed heat pump dryers should be designed according to the following “design rules”: [Strømmen, 1999]

- Drying operation with optimum bed height to obtain a high relative humidity at the dryer outlet
- Stable fluidisation due to the sorption characteristics of the material being dried
- Continuous, not batch operation, due to the lowering of capacity and efficiency during a batch process
- As high inlet temperature in the dryer as possible, due to the improved thermal efficiency and capacity
- As low refrigeration capacity as possible, as long as the desired production is achieved (over-sizing will increase dh/dx and reduce SMER)
- The choice of evaporating and condensing temperature of the heat pump should be the combination giving the best combination of COP and dh/dx (an optimum might exist).

The energy consumption in an a continuous heat pump dryer operated in a combined drying mode at temperatures at –5°C in the first stages and at 30°C at the second stage can be calculated from the following equation:

$$SMER = (COP_{LT}/(dh/dx)_{LT})*(\tau_{LT}/\ \tau_{tot}) + (COP_{HT}/(dh/dx)_{HT})*(\tau_{HT}/\ \tau_{tot}) \qquad (3)$$

The following reference process in the Mollier humid air diagram is used:

Table 1: Process conditions for the heat pump drying operated at combined drying mode

	LT	**HT**
Air inlet drying temperature	-5 °C	30 °C
Air inlet relative humidity	40%	40%
Air outlet relative humidity	80%	80%
Surface temperature of air cooler	t_{dp} - 5°C	t_{dp} - 5°C
Heat pump evaporating temperature	air cooler surface temperature – 2°C	air cooler surface temperature – 2°C
Heat pump condensing temperature	air inlet drying temperature + 5°C	air inlet drying temperature + 5°C
Heat pump refrigerant	NH_3	NH_3

The results of the calculations are shown in the Figures 8 and 9. Drying at –5°C for 10 hours will give a lower bulk density, a higher rehydration ability and an energy consumption 7.5 times higher than drying at 30°C only. The SMER for the combined drying at 10 hours at –5°C will be reduced with 67% of the SMER at 30°C.

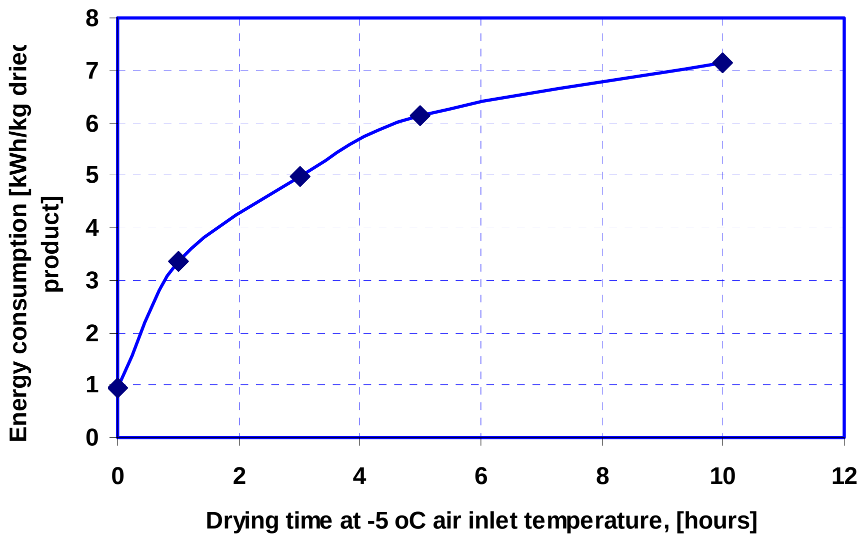

Figure 8: Dryer energy consumption per kg dried cod pieces with increasing time at –5°C

Fig 8 and 9 clearly indicates that the energy efficiency is decreasing as the drying time at –5°C increasing. The consequences on the plant size are also considerable. The drying capacity of the plant is given by:

$$P = M_{air\,-5^{o}C} * \Delta x_{-5^{o}C} = M_{air\,+30^{o}C} * \Delta x_{+30^{o}C} \qquad (4)$$

If the plants is designed to be operated at m-5oC or +30oC with the same water removal capacity the needed air flow will be considerable higher at –5oC compared to +30oC,

in both cases

$$\frac{M_{air-5°C}}{M_{air+30°C}} = \frac{\Delta x_{+30°C}}{\Delta x_{-5°C}} \tag{5}$$

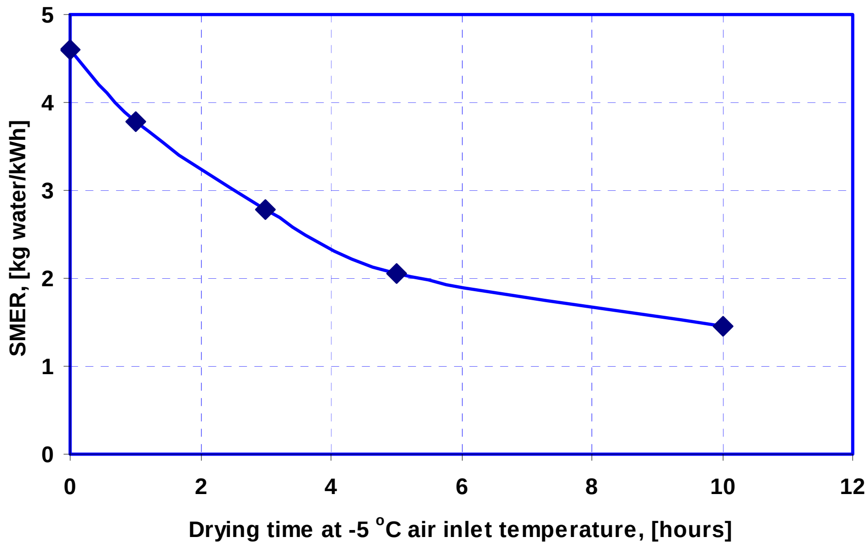

Figure 9: SMER for dried pieces of cod with increasing drying time at –5°C

If the $\varphi_{inlet}/\varphi_{outlet}$ of drying chamber is 40/80% The volume flow needed at –5°C compared to +30°C will be approx 300% higher compared to +30°C due to the much lower Δx at –5°C. The volume flow (m^3/s) will also decide the plant size of the air system if the plant is operated in a combined mode with initial freeze drying.

5 Conclusions

Heat pump dryers have an energy consumption 60 – 80 % lower than other dryers operating at the same temperature. Typical SMER is in the range 2–5. When operated at a combined drying mode with an initial freeze drying step the SMER can go down to a value of 1 kgH_2O/kWh depending on the time period at freeze drying temperatures. In such cases plant size will also increase considerably compared to drying at 20°C or higher.

Drying at 20°C or in a combined mode with initial freeze drying have shown a considerable increase in quality for several food products and chemical pulp. Industrialisation of atmospheric heat pump freeze drying are now being realized for several vegetable products. Promising results on chemical pulp will be followed up by further research.

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Nomenclature

dh_{opt}	Optimal enthalpy difference for air cooler	[kJ/kg dry air]
SMER	Specific Moisture Extraction Rate	[kg water/kWh]
COP	Coefficient of performance	[-]
dh/dx	Thermal efficiency	[kJ/kg dry air]
LT	Low temperature	[^oC]
HT	High temperature	[^oC]
τ_{LT}	Residence time at low temperature	[s]
τ_{HT}	Residence time at high temperature	[s]
τ_{tot}	Total residence time	[s]
dp	dew point	[^oC]
M_{air}	Mass flow of air	[kg/s]
x	Abs. humidity of air	[kg water//kg dry air]
φ	Relative humidity for air	[%]
P	drying capacity	[kg water/s]