CARBON-DIOXIDE HEAT PUMP DRYER AND MEASUREMENTS ON COEFFICIENT OF PERFORMANCE AND SPECIFIC MOISTURE EXTRACTION RATIO

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ABSTRACT

A new prototype fluidised bed heat pump dryer with CO_2 as the working medium is constructed and build at the Dewatering R&D Centre at SINTEF and NTNU. The dryer is designed to use different inert gasses in the drying chamber, also included to run in under and over atmospheric pressure. This opens up for possibilities to test product under different conditions and investigate influence on the heat and mass transfer during the drying. The drying chamber can be changed and can operate in both fluid bed and static bed, and can be run in continues and batch operations. The options of the drying chamber gives possibilities to dry granulates or peaces/particles, foamed products, and liquids. It is also possible to coat, granulate particles and to agglomerate new particles.

To meet hygienic regulations the plant is build in stainless steel with CIP washing system, including 2.2 bar steam for sterilising.

The heat pump circuit is constructed to use CO_2 as working media with maximum working pressure of 130 bars. To operate in a wide range of temperatures (–30 ^oC to +110 ^oC) in the drying chamber the heat pump process will operate in a traditional way with evaporating and condensing mode, in a transcritical mode and also in a pure gas mode at high temperatures. These running conditions are depending of the product and its sensitivity of heat. This paper will describe prototype tests and measured coefficient of performance and specific moisture extraction ratio. The paper describes how the dryer is build and the possibilities to use CO_2 as refrigerant for energy savings and the operating temperature levels.

INTRODUCTION

The traditional way to dry biological materials is to use vacuum freeze dryers or hot air dryers. Vacuum freeze dryers have relatively high investment and are energy demanding but gives high quality products. Warm air dryers have lower investments with drying temperatures in the range of 50-80^oC. For the air dryers the drying air temperature has to be raised high above the ambient temperature to have a drying potential. The drying potential in these dryers are influenced of the variations in relative humidity and temperature of the ambient air during the day and over the year. Temperature level and variations gives lower qualities and the products have a lower price than freeze dried products.

Systems using heat pumps can operate at temperature levels independent of ambient air, and the temperature level is given depending of the quality requested from the market. It gives the possibility to make a closed loop where the evaporator removes the humidity form the air and the condenser gives the air the optimal temperature and relative humidity. The energy removed from the air in the evaporator is returned to the air in the condenser. The drying circuit are in energy balance. Energy to run the fan and the heat pump compressor has to be rejected in an external condenser (heat exchanger). Energy consumption in an air dryer with heat pump is between 20-30% of a normal air dryer. Heat pump dryers are environmental friendly and energy saving plants.

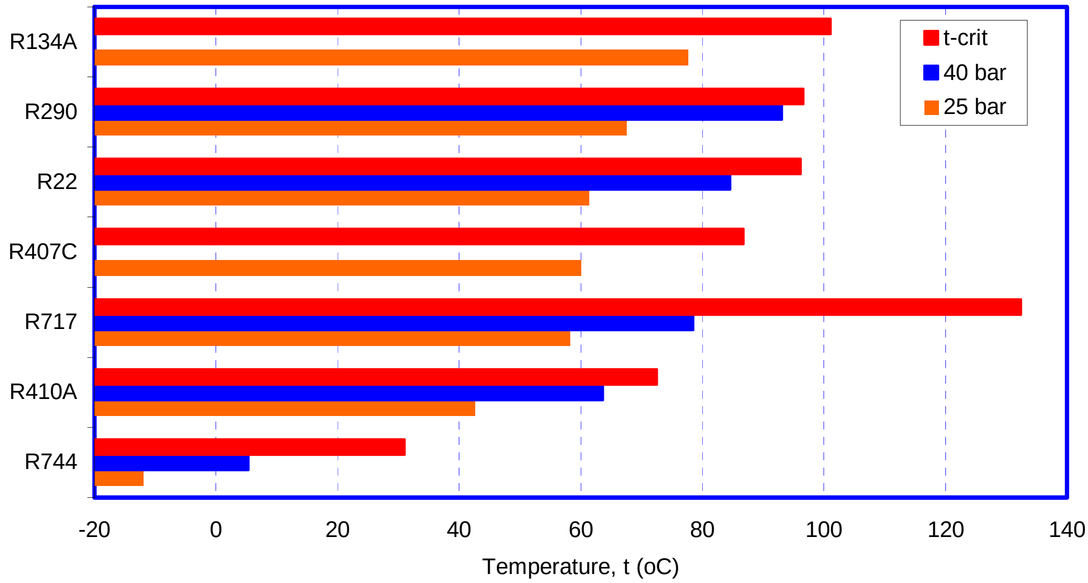


Figure 1. Critical and condensing temperatures for different heat pump working fluids at pressure of 25 and 40bar

Traditionally heat pump driers are built with refrigerants limited to 25 or 40 bar pressure in the refrigeration circuit. This gives limitations of the temperature level for the air inlet temperature for the drying chamber. Figure 1 shows critical temperature and condensation temperatures at 25 and 40 bars for the most common refrigerants in heat pumps.

As shown in figure 1 most of the refrigerants have a maximum temperature between 40 and 60^{o}C at 25bar. This means that the dryer cannot operate at higher temperatures than between 35 and 55^{o}C depending of the chosen refrigerant.

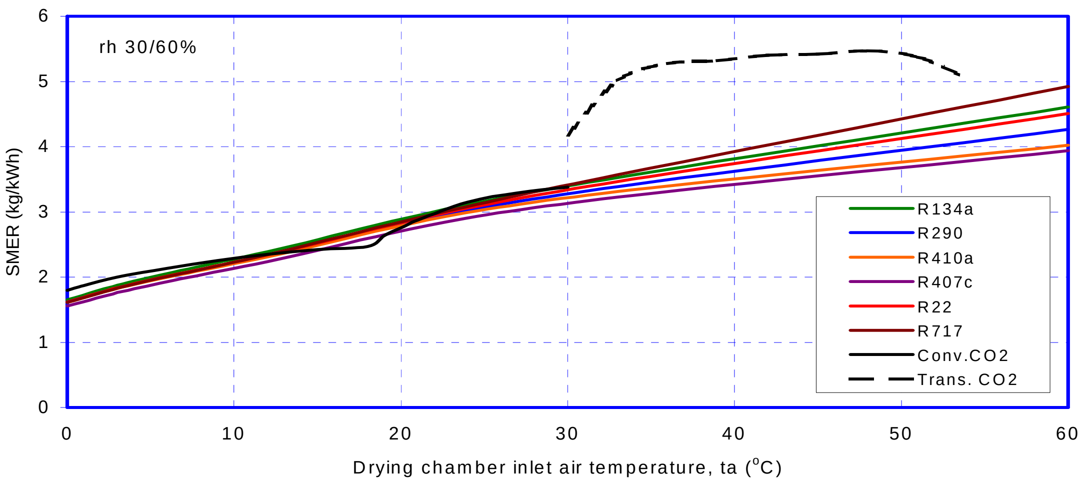


Figure 2. SMER as a function of air inlet temperature to drying chamber

To compare dryer performance the Specific Moisture Extraction Rate (SMER) gives a good reference for the efficiency. This number shows how much water removed from the product compared to the energy use for the plant (kg water/kWh). In figure 2 the SMER for the same refrigerants are shown. For all refrigerants it is calculated with the same evaporating and condensing temperature. The compressor isentropic efficiency is calculated from the same equation depending on the pressure ratio. For the CO_2-process at temperatures above the critical pressure the process is calculated with a traditional transcritical process.

The calculations are based on the same moisture removal rate from the product. Figure 2 gives an indication of the energy efficiency of the process. At low temperatures the CO_2-process have a better performance than the other refrigerants. When the CO_2-process reaches the transcritical phase we can see that the process will be much better in the temperature interval between 20-50°C. At drying chamber temperatures of 35 to 50°C the process is about 30% more energy efficient.

The dryer running under continuous fluid bed operation mode and the SMER and COP are calculated from the following equations. The drying chamber air inlet temperature is varied and the relative humidity in and out from the chamber is held constant.

The refrigeration capacity:

$$Q_o = G_a(h_o - h_c) = G_a dh \qquad [\text{kW}] \qquad (1)$$

where G_a is the air flow in the system. The energy use for the plant is calculated with the following equation:

$$W_c = \frac{Q_o}{dh_{re}} \times \frac{dh_{is}}{\eta_{is}} \qquad [\text{kW}] \qquad (2)$$

where η_{is} refers to the compressor isentropic efficiency. The compressor isentropic efficiency is a function of the compressor pressure ratio.

The coefficient of performance for the plant is given from the following equation:

$$COP = \frac{Q_o}{W_c} \qquad [-] \qquad (3)$$

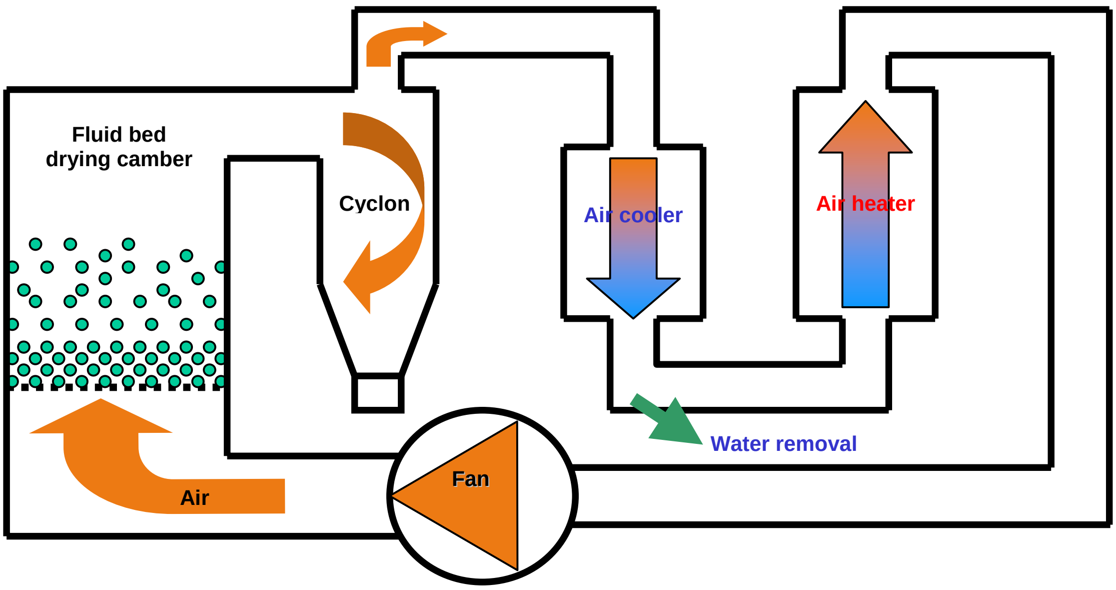


Figure 3. Principal drawing of the fluid bed dryer with heat pump and CO_2 as refrigerant

SMER (specific moisture extraction rate):

$$SMER = COP \times \frac{dx}{dh} \qquad \text{[kg water/kWh]} \qquad (4)$$

In the calculations there have been used thermodynamic data for moistured air in the library HxLib and thermodynamic data for refrigerants from RnLib, connected to a worksheet model.

In the Dewatering Laboratory at NTNU and SINTEF there is built a new prototype fluid bed heat pump drier with CO_2 as the refrigerant.

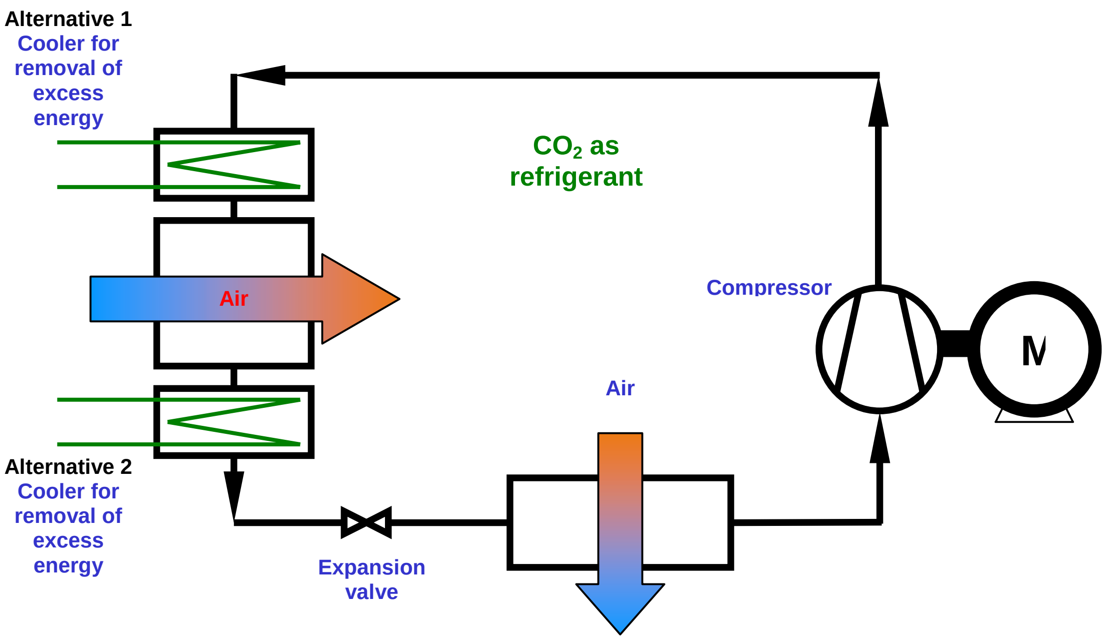


Figure 4. Principal drawing of the CO_2 circuit for the heat pump

Figure 3 and 4 shows the principal drawing of the air circuit and the heat pump circuit, and the figure 5 shows a picture of the plant. The drier is built to run experiments with different kinds of raw materials such as particles, foamed frozen particles and liquids. The fluid bed is also built to handle agglomeration. The dryer circuit is gas tight up to 2.2bar. This gives possibilities to operate with inert gas in the drying chamber. This gives also possibilities to dry products with under and over atmospheric pressure and to investigate the influence on the heat and mass transfer of the product during the drying process and the influence of the quality of the final dried product. The drying chamber has a bed area of 0.07 m^2 and a variable airflow from 1 to 3 m/s. The plant is equipped with a cyclone to separate small particles. All materials in contact with the product are in stainless steel. To clean the plant it is equipped with CIP washing system and in addition it is also equipped with steam nozzles for sterilisation at 2.2bar.

In the drying circuit the air is cooled in the air cooler and the moisture in the air is removed. To make a dry air the energy removed from the air in the air cooler is reentered to the air in the air heater. The drying circuit is a zero energy system. The energy used to pump the air around and the energy to the compressor has to be removed externally. This is done in the two coolers for excess energy. These two coolers are run in two alternative modes. Alternative 1 is used at low temperatures in the dryer, and alternative 2 for temperatures above 40°C in the dryer.

DISCUSSION

The first initial test has been run in the drier. The drying product in these test have been peas. The drying temperature has been set to +30°C. The plant is operated after alternative 1 mode with the removal of the excess heat at high temperature.

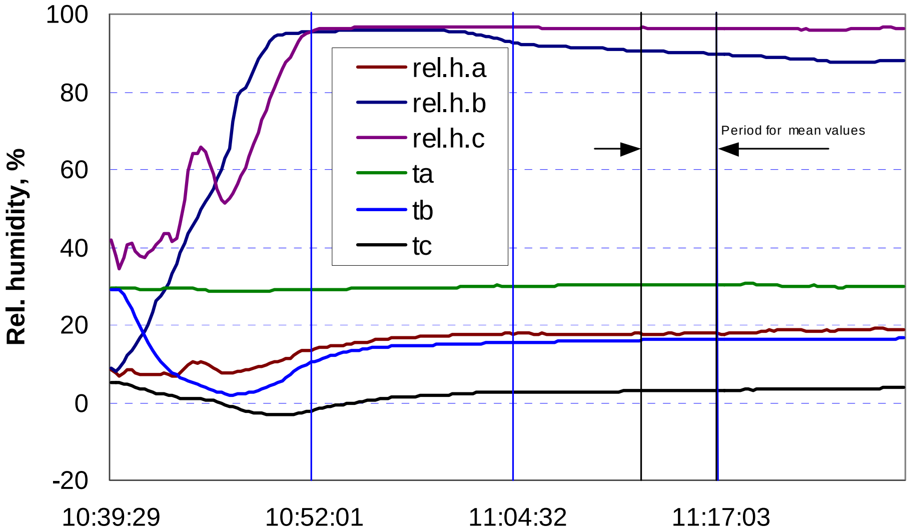


Figure 5 Relative humidity and temperatures for the drying process by time

From the measured period there have been calculated mean values for the plants efficiency for the given period as shown in figure 5. Figure 6 shows the compressor inlet and outlet pressures and the corresponding temperatures.

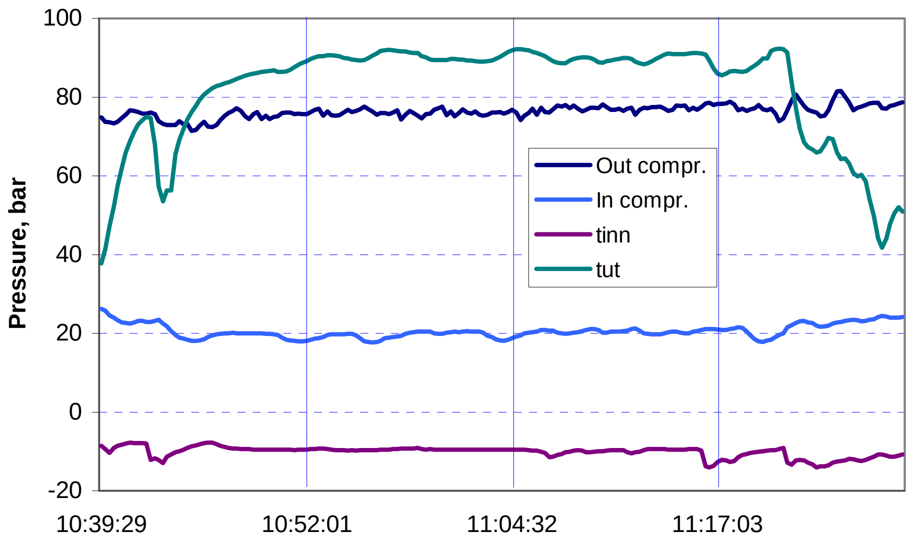
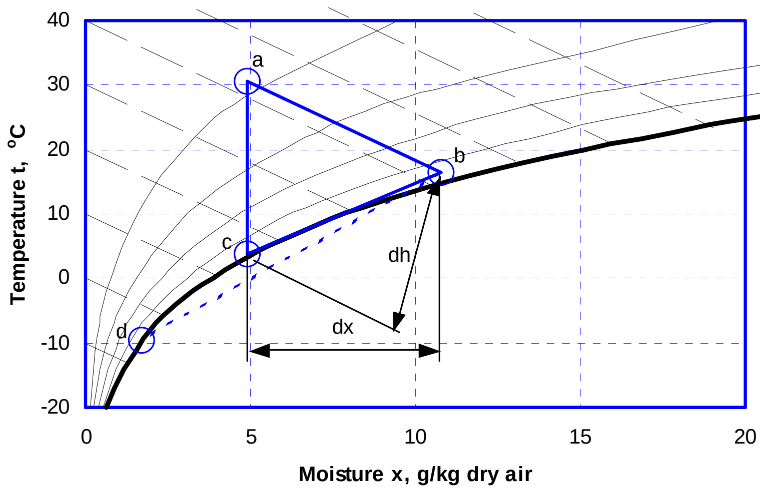


Figure 6 Pressure and temperatures in and out of the compressor by time

The compressor uses in the plant is a Dorin compressor with swept volume of 2,7 m3/h. The heat exchangers are made of stainless steel with tubes without fins to be easily cleaned. The external heat exchanger is cooled by water. The first test shows the SMER of 2,5 at 30oC in the drying chamber. This is lower the expected. The energy efficiency of the plant was measured to 3,5. This is initial value and the dryer will be modified to obtain higher rates during the next months.



Firgure 7 Mollier diagram for the humid air in the drying process

Figure 7 shows the air process in the Mollier diagram. The surface temperature in point d is the average temperature for the cooler.

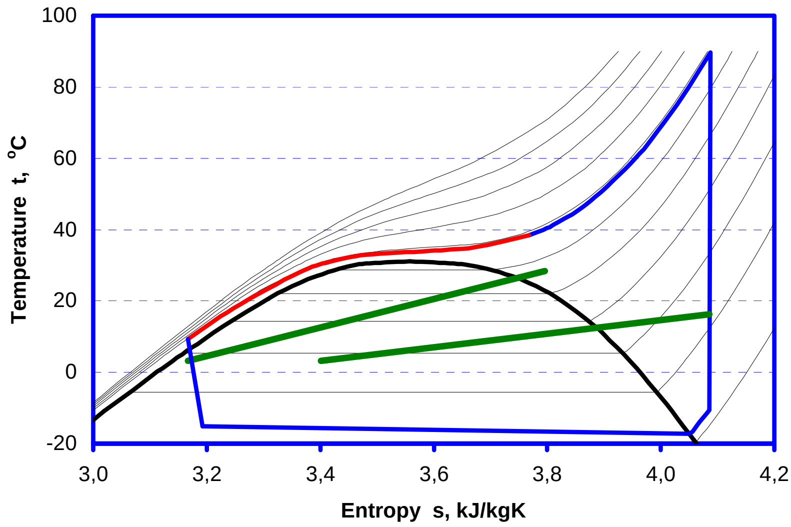


Figure 8 Temperature entropy diagram for the CO_2-process

In figure 8 the red coloured line is the cooling of CO2 in the air heater. The temperature adaptation to the heating of air in this type of heat pumps, are better than the heating of the air with constant temperature of the refrigerant as in the traditional dryers.

CONCLUSIONS

An innovative fluidised bed heat pump dryer with carbon dioxide as working fluids is designed and built at the dewatering R&D Laboratories at NTNU and SINTEF in Norway. The working fluid circuit is designed for maximum pressure of 130 bar. The dryer is designed for inert gas or air, for CIP system and the drying circuit stands 2.2bar absolute pressure for sterilization purpose. The dryer operates in fluidised or static beds, continuous or batch, and handles granular solids, semi-solids or solutions. Besides drying, this equipment is able to perform multiples tasks of coating, granulation and agglomeration. The drying medium inlet temperature can be set to wide range from –30 to +100°C, which can be set according to the product thermal sensitivity.

The coefficient of performance, refrigeration capacity and specific moisture extraction rate were computed for the conventional and the transcritical cycle at different drying conditions. The first test have be run and the initial data for the dryer at SMER = 2.5 and the COP = 3.5 at 30°C drying temperature. This is initial value and the dryer will be modified to obtain higher rates during the next months. The use of CO_2 as refrigerants gives higher value than the other common heat pump refrigerants in almost all temperature levels.

NOMENCLATURE

COP	Coefficient of performance
dh	Specific enthalpy for heating and cooling of air, kJ/kg
dh/dx	The dryer thermal efficiency
dx	Air dewatering rate, kg water/kg dry air
G_a	Air flow, kg/s
G_r	Refrigerant flow, kg/s
h	Enthalpy for moistured air, kJ/kg
η_{is}	Compressor isentropic efficiency
Q_o	Refrigeration capacity, kW
RH	Relative humidity for air, %
SMER	Specific Moisture extraction rate, kg water/kWh
TC	Transcritical process
W_c	Compressor energy consumption, kW
HxLib	Thermodynamic library for moistured air
RnLib	Thermodynamic library for refrigerants

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