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### ECOLOGICALLY FRIENDLY TECHNOLOGIES OF THE 21ST CENTURY (USING THE DRYING PROCESS AS AN EXAMPLE)

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Abstract: This paper covers the advances in heat pump drying technologies for the twenty-first century. These dryers operate with high thermal effectiveness for manufacturing superior quality product and features benefits to environment, climate change and process sustainability. Descriptions and layouts are given on design of heat pump dryers operating in single and multi stage vapor compression and drying chambers placed in series. The drying modes covered are atmospheric sublimation and evaporation for improved capacity and superior characteristics of dried materials. The future trend is heat pump drying with natural fluids to comply with regulations to reduce environmental problems such as global warming and climate change. These technologies have been built and extensive R&D have been done at Norwegian University of Science and Technology in Trondheim. The technology has progressed to pilot scale and industrial applications contributing to a better 21st Century.

Keywords: design, energy efficiency, environment, heat pump drying, layout, sustainability.

Cooling and heating processes have been around for several decades but modern heat pump dryers (HPD) incorporating precise instrumentation and controls have only recently advanced from pilot to industrial applications.

The future HPD will operate with natural working fluids to comply with current environmental protection protocols. The focus on HPD has been on capacity, efficiency, sustainability and design for operation with environmentally friendly fluids. HPD allows processing of heat-sensitive materials and produce high quality powders with tailored properties at competitive cost. In this application, the HPD operates in atmospheric freeze-drying and evaporative drying in a single unit.

This paper covers HPD design with natural fluids and compares dryers based on coefficients of performance, thermal efficiency and specific moisture extraction ratio. Several arrangements of heat pump dryers are illustrated with bench units, pilot and industrial plants.

HPD is an innovative technology for the 21st Century and its unique performance leads to social-industrial and cost-efficiency advantages. The conventional dryers, still in common use today, lack these benefits since they were design in a time when environment and energy were unimportant issues [1].

## Environment and climate aspects related to drying

Conventional dryers consume large amounts of energy inducing an equivalent emission of green house gas (GHG) to the atmosphere.

The cause of radiation blockage is the notorious greenhouse gases (GHG) represented mainly by carbon dioxide, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluoro-carbons (HFCs), hydrocarbons, methane and nitrous oxide.

The main process involved in this oxygen, water and carbon dioxide mass balance is photosynthesis that is triggered by those sun's photons that successfully cross the atmosphere and strike green leaves. Here carbon dioxide combines with water producing carbohydrate and oxygen molecules. Photosynthetic plants and organisms are converters of GHG to compounds essential to life and respiration. A disturbance of the oxygen-GHG mass balance results in an over-heating of the biosphere with appalling effects in the hydrological and carbon dioxide-air cycles.

However, GHGs are being released in increased concentration by direct combustion processes, transport, agriculture, wastes, and chemicals-solvents and other industries.

The most extensive initiative to reduce the GHG emission occurs in Europe through proposals and incentives. The artificial emission of GHGs in 2011 was estimated at 33.4 Gt, a number that is difficult to grasp. A better sense of this magnitude is to convert to a familiar geometrical shape. Since the density of carbon dioxide is about 1.98 kg/m3 the emission is equivalent to a sphere of   
32 km in diameter.

There are also chemical substances degrading the living space stratosphere and an indicator is the ozone depletion potential (ODP). The 1920's conception of the CFCs and HCFCs was followed by their widespread use in commercial refrigeration and aerosol agents [2].

Moreover, observations and measurements made at the end of last century indicated that the chlorine molecule in CFCs and HCFCs is highly stable and causes severe damage to the ozone layer. As a consequence CFCs and HCFCs were phased-out and replaced by HFCs that have zero ODP and non-zero global warming potential (GWP).

Fortunately, climate change or environment depletion can be avoided by selecting the best refrigerants and heat pump fluids. These are natural fluids with near zero global warming potential and zero ozone depletion potential.

Briefly, heat pump drying can be designed to operate with natural fluids resulting in a significant drop in green house gas emission. In particular, when electricity is generated in fossil fueled thermal power plants, the heat pump technology provides reduction in energy consumption with an equivalent drop in greenhouse gas emissions. Furthermore, the heat pump dryers operate in closed cycles both in the refrigerant and drying air loops. This means that it is a green technology without environmental pollution by fines or thermal pollution by hot exhaust air.

## Heat Pump Drying Benefits And WORKING Principle

Conventional dryers have limitations such as low quality dried product, negative environmental impact and high energy consumption or high cost. A solution to these problems is to apply heat pump drying that is currently a ready-to-use technology. It operates well at a wide range of temperatures that can be set according to the material thermal sensibility and applications. It can also combine low and medium temperatures in a single heat pump dryer aiming at energy savings and superior product quality [3].

**Table 1. Energy utilization by the main conventional and by heat pump dryers**

|  |  |  |
| --- | --- | --- |
| Dryers | SMER, kg/kWh | Specific energy, kJ/kg |
| Conventional dryers:   * rotary, spray, tunnel and fluidized bed * vacuum freeze | 0.5 to 0.75  0.08 | 7200 to 4800  – |
| Adiabatic heat pump fluidized bed dryer | 2 to 3 | 1800 to 1200 |
| Polytropic heat pump fluidized bed dryer | 3 to 5 | 1200 to 720 |
| Superheated steam dryer | 2.4 to 3.6 | 1500 to 1000 |

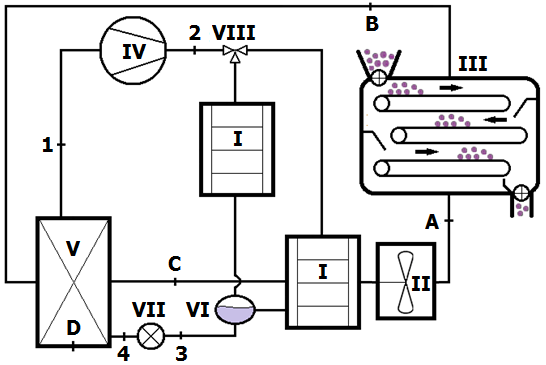
A properly designed heat pump dryer uses less energy than what is required by conventional dryers. Table 1 gives the energy utilization by main conventional and heat pump dryers [4]. It indicates that the HPD is several orders-of-magnitude more energy efficient and less costly than conventional dryers. It also shows that the adiabatic and polytropic heat pump dryers have SMER similar or slightly higher than superheated steam dryer.

The heat pump dryer recovers energy from the drying exhaust vapor, which is lost in open conventional dryers. A properly designed heat pump dryer has a closed loop and fully recovers energy that is re-distributed for heating and cooling as required in a drying process. The refrigerant flows through the evaporator where it absorbs latent heat from the changing phase exhaust vapor and recycles it to the condenser. In a similar way valuable volatiles can be recovered and harmful condensable vapors can be separated and discarded.

## SINGLE STAGE VAPOR COMPRESSION HEAT PUMP DRYING

The single-stage vapor compression is a commonly applied heat pump cycle. In this case only one evaporator cools the moist air, condenses the water vapor fraction and absorbs (for boiling the refrigerant) the corresponding latent heat of vapor condensation [3].

A single vapor compression system has a throttling valve or similar device separating the low and high pressure sides as illustrated in Fig. 1.



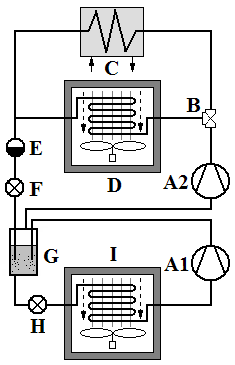
**Fig. 1. Heat pump belt dryer with R134a: I – condensers (heaters), II – blower, III – belt dryer with leek cubes, IV – compressor, V – evaporator, VI – receiver, VII – throttling valve,   
VIII – three-way valve, 1 – saturated vapor, 2 – superheated vapor, 3 – saturated liquid,   
4 – vapor and liquid mixture, A – inlet of drying chamber, B – inlet of evaporator, C – inlet of condenser, D – evaporator surface.**

Heat exchangers particularly called condensers and evaporators are applied to transfer energy between the heat pump system working fluid and surroundings. The working fluid changes phase from vapor to liquid as it flows through the condenser and releases energy to the drying air acting as heat sink. This direction of energy transfer requires a higher temperature in the heat pump fluid than the heat sink. Simultaneously, the working fluid changes phase from a liquid-vapor mixture to vapor by boiling in the evaporator while receiving energy from the moist-air as heat source. This energy transfer also requires a lower temperature in the evaporating fluid than in the heat source. These processes take place in a closed cycle as the working fluid flows through condensers, evaporators, compressors and throttling devices.

The single stage vapor compression heat pump dryer applies with high coefficient of performance (COP) and specific moisture extraction ratio (SMER) for medium temperature drying. The COP and SMER are particularly high for heat pump drying systems with medium or small temperature difference between evaporation and condensation.

## two stage vapor compression heat pump drying

A single stage heat pump drying system is advantageously and widely applied but is unable to provide several streams of drying air with different conditions and to operate with large evaporating and condensing temperature difference [5]. For this case the solution is multistage heat pump drying as illustrated in Fig. 2.



**Fig. 2. Two-stage heat pump dryer: A1/A2– low and high stage compressors, B – three-way valve, C/D – external and internal condensers, E – receiver, F – float valve, G – flash-tank,**

**H – throttling valve, I – evaporator.**

This figure shows a two-stage heat pump dryer that operates with large evaporating and condensing temperature difference and provides two air streams with different conditions. The liquid refrigerant flows from the condenser D and is collected in a receiver E, then, it moves through the float valve F and is collected in the intermediate pressure flash-tank G. At the same time this tank receives intermediate pressurized superheated vapor from the first stage compressor A1. In the tank G the refrigerant is separated into two phases, one is saturated liquid that enters the throttling valve H connected to the evaporator I and changes phase to enter the low stage compressor A1. The other phase is saturated vapor that flows to the suction line of the high stage compressor A2. This compressor discharges superheated vapor to the three-way valve B that directs vapor to the external and internal condensers C and D, respectively.

The second stage drying involves moisture removal by evaporation at higher rates. The two-stage heat pump dryer operates with energy recovery for high efficiency (superior quality dried product) resulting in using less energy and reducing costs [6]. A properly designed two stage vapor compression heat pump dryer has better performance than single stage vapor compression for large temperature and pressure differences between evaporation and condensation. The reason is that the extra components in the dryer allows operation in smaller pressure intervals leading to enhanced coefficients of performance, energy utilization and water removal rate. A major advantage of this dryer is its ability to process heat sensitive wet-solids, liquid and pastes since the evaporator and air inlet temperatures can be set slightly below the material freezing point [7]. The outcome is high quality product while operating with high performance and enhanced water removal rates. The additional benefits of this heat pump dryer are lower pressure ratio, higher cooling capacity, higher isentropic efficiency, lower discharge temperature or compressor overheating protection, lower compression and expansion energy losses.

## selection of heat pump fluids

There is an abundance of heat pump fluids, or refrigerants, in the international market today because there is no ideal refrigerant satisfying all required conditions in different applications [8]. A question is: how to select a fluid from this wide variety? What are the criteria for selection? Then, let's gradually answer these questions. The selection procedure involves comparison of fluids based on properties at different state points of the heat pump cycle and at specific operating conditions. The current selection favors fluids with near zero ozone depletion potential and global warming potential, harmless and non-toxic, compatible with materials and lubricating oils, favorable properties and low cost.

### Selection Based on Performance and Cycles

The performance determination must be made from cycles with similar operating conditions. A heat pump and refrigerator operates in a cycle with a fluid or refrigerant that flows through the evaporator absorbing energy from the heat source (medium to be cooled) and through the condenser transferring energy to the heat sink (medium to be heated). The processes in a mechanical vapor compression heat pump system cycle are evaporation, condensation, compression and throttling. These processes and energy transport occur as the fluid changes phase and flows through the components leading to exchange of energy with the heat source and sink.

### Selection Based on Performance at Transcritical Cycle

An important factor in selecting a fluid is its ability to proper operate in a transcritical cycle. This cycle has improved performance compared to a subcritical cycle operating close to the critical point. In a conventional subcritical cycle the condensation occurs in the two-phase region and the COP drops sharply as the pressure approaches the critical point. The obvious questions are how to reverse this situation and which fluid to select? The situation is inverted by considering that condensation in a transcritical cycle (above critical point) happens without phase change and, as the condensation pressure approaches the critical point, the COP greatly increases by means of gas cooling. An exceptional fluid choice for the heat pump transcritical cycle is the carbon dioxide (R744). This is because it has critical temperature and pressure of 31.03oC and 7380 kPa, which is suitable for medium temperature drying. The heat pump with carbon dioxide in a transcritical cycle displays better performance characteristics compared to subcritical cycle.

### Selection Based on Operating Pressure and Temperature

The refrigerant can be selected based on its properties related to evaporating and condensing temperatures. The HP system is usually designed for limiting pressure of 25 bar, which is the typical value for manufacturing commercial compressors. The temperature and pressure are constant in the two-phase region for azeotropic blends and natural fluids, which means a constant saturation temperature at a given pressure. However, the temperature varies with the pressure for zeotropic blends and air. This implies that, for these blends, the temperatures at each pressure are defined by bubble-point temperature (tbub) and dew-point temperature (tdew) rather than saturation temperature (tsat).

The R718 has high saturation temperatures at the typical pressures and is seldom used in vapor compression heat pump systems. In contrast, R729 is a cryogenic fluid with very low saturation temperatures at the given pressures. Natural fluids have a large variation of the saturation temperatures allowing a wide range of applications. The closeness of the bubble-point temperatures of the zeotropic blends indicates their similar purposes and performances.

### Selection Based on Effect on Safety and Environmental Issues

The selection of the heat pump fluid can be made based on its environmental effects and its potential health risks.In terms of safety the refrigerant selection depends on classes and groups established according to the Standard 34 [9]. Safety classes of refrigerants are expressed by letters: A: nontoxic for concentration below 400 ppm by volume, B: toxic at concentration above 400 ppm.

Climate change and environmental impact are minimized by selecting fluids with low GWP. The GWP is equivalent to the amount of heat trapped as greenhouse gases (GHGs). The GWP value is relative to carbon dioxide, which is a reference value equal to 1.

## **INNOVATIVE HEAT PUMP DRYERS WITH NATURAL FLUIDS DESIGNED AT NTNU**

The current trend favors zero ODP and zero GWP fluids and the future vision is intensified application of natural fluids in heat pumps and refrigeration systems. Then, R&D is increasing and encouraging the use of natural fluids in combination with today's advanced components, processes, controls, and materials. The reasons are that natural fluids have excellent properties and are permanent solutions concerning safety and impact to environment and climate change. Natural fluids are further sub-divided into safest, such as water and air, and practical which are the hydrocarbons, ammonia, and carbon dioxide.

These R&D efforts are being intensified because the collective advantages of natural fluids have attracted several institutions and industries that are currently engaged in developing these heat pump systems. In choosing the natural fluids alternatives, ammonia and carbon dioxide were considered the best selection due to the benefits of zero ODP, unit GWP, safety, proper temperature and pressure levels, excellent performance and energy utilization. Process performance and impact on environment, climate and health have been the focus of R&D at the Norwegian University of Science and Technology (NTNU). And as a consequence, several heat pump dryers with R717 and R744 have been designed and built. In addition to fluid another choice was a full recirculation of exhaust air and maximum energy recovery by the heat pump dryer components. These parameters are considered in the design of the R717 and R744 heat pump dryers and, in particular, the specifications of the drying chamber, blower, evaporator, compressor, condenser and throttling device. The main vision is to develop sustainable and green heat pump technology to achieve enhanced coefficient of performance and optimum specific moisture extraction ratio.

### Carbon Dioxide Heat Pump Dryer

The only pilot scale heat pump dryer working with carbon dioxide in a transcritical cycle for particulate materials in a fluidized or stationary bed has been built at NTNU (Fig. 3).

The R744 heat pump dryer is designed to operate at variable conditions with a cleaning in place system (CIP). The CIP includes spray nozzles that are mounted in the drying loop allowing proper cleaning of the blower, cyclone, heat exchangers, drying chamber and connecting ducts prior and after drying. Air and gases such as nitrogen, helium and steam can be applied for drying or sterilization since drying loop is designed to stand a maximum absolute pressure of 220 kPa.

Potential applications for this dryer are biochemical, chemical, medical, pharmaceutical and food products. The wet material is loaded into the chamber, the gas velocity is adjusted for fluidization or stationary modes and the temperature is set according to the nature, stickiness and thermal sensitivity of the drying material.

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**Fig. 3. The pilot scale heat pump dryer operating with R744 in transcritical cycle:   
1 – cyclone, 2 – drying chamber, 3 – condenser, 4 – evaporator, 5 – adjustable external condenser, 6 – control panel, 7 – compressor, 8 – cleaning in place system.**

Major benefits of this heat pump dryer are: (a) it is a green technology because it has zero ODP or near zero GWP, (b) it has a high coefficient of performance and (c) it operates with high energy efficiency and lower cost.

### Ammonia Heat Pump Dryer

Ammonia was selected as the natural fluid and used in the fluidized bed and tunnel drying technologies designed and built at NTNU. The fluidized bed heat pumpdryer working with R717 differs from the conventional adiabatic dryers because it is designed to operate close to isothermal or non-adiabatic processes. To achieve this operation the air drying loop side has two drying chambers with immersed heat exchangers connected to the heat pump condensers. The wet material is continuously loaded into the first drying chamber operating in back-mixing fluidized bed, after which the semi-dried product flows through a connecting duct and enters the second drying chamber operating in plug-flow where it is fully dried and discharged.

## CONCLUSIONS

HPD is a green technology with zero GWP and ODP when operating with natural fluids. A well designed heat pump dryer is several orders-of-magnitude more energy efficient and less costly than conventional dryers. HPD beneficially contribute to a sustainable society while providing superior products at competitive cost. This is an advanced engineered drying technology ready for implementation by modern industries wishing a return of investment while contributing to a sustainable society.

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