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Energy Effective and Green Drying Technologies with Industrial Applications

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Heat pump drying is a green technology with zero global warming potential and zero ozone depletion potential when operating with natural fluids. A well designed heat pump dryer can be several times more energy efficient and less costly than conventional dryers. This dryer beneficially contributes to a sustainable society while providing superior products at competitive cost. It is an advanced engineered drying technology ready for implementation by modern industries wishing a return of investment while contributing to a sustainable society. This paper covers the advances in heat pump and superheated steam drying technologies. These drying processes are in the category of green technologies because they are highly effective and advantageous for the environment and climate change. Descriptions and layouts are given covering design of heat pump and steam dryers. Details are provided in their beneficial operation in single and multistage with 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 and superheated steam drying complying with proper industrial practice and with regulations reducing damage to sea, soil and water as well as zeroing contribution to global warming and to climate change. These technologies have been built and extensive R&D has been done at Norwegian University of Science and Technology in Trondheim. The technology has progressed to pilot scale and industrial applications indicating a small but real contribution to a better society today and tomorrow.
Lastly, this is an advanced engineered drying technology ready for implementation by modern industries wishing a return of investment while preserving the environment.

1. Introduction

Advanced heat pump dryers with accurate control is a recent technology that has evolved from pilot to industrial applications in Norway.

The next generation of dryers will be designed to be thermally efficient while operating with natural working fluids to keep undisturbed the earth's climate and environment. In this way heat pump dryer (HPD) is designed focusing on capacity, efficiency, sustainability and operation with environmentally friendly fluids. Heat-sensitive materials and non-sensitive wet solids are converted to high quality powders tailored for better properties at competitive cost. Additionally, a single heat pump dryer can operate in atmospheric sublimation and evaporative modes (Alves-Filho et al., 2008; Alves-Filho and Roos, 2006).

This paper covers heat pump dryers design and how to use natural fluids and comparison is made considering coefficients of performance, efficiency and rate of moisture removal. Layouts of some heat pump dryers illustrate the evolution from bench scale, pilot to industrial plants.

HPD has potential to be a leading technology socially and industrially beneficial due to cost, efficiency and quality. Consistently, this technology has progressed to pilot scale and industrial applications indicating a small but real contribution to a better society today and tomorrow (IEA, 2013).

An important consideration in new dryer design is environmental and climate impact. Classical dryers consume large amounts of energy and contribute to emission of greenhouse gas (GHG) to the atmosphere and disturbance to climate.

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Photosynthetic plants and organisms convert carbon-dioxide, a GHG, to compounds essential to life and respiration. Disturbance of GHG in the atmospheric mass balance leads to biosphere over-heating and negative effects on the hydrological, carbon-dioxide-oxygen or air cycles.

The emission of GHGs problem is expected to sharply increase in the next decades. This is because some strong economies are indifferent to the problem while the most populous countries fiercely compete for markets and are able to prodigiously increase their often-polluting manufacturing output.

Measurements have indicated that the stable chlorine molecule in chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) causes damage to the ozone layer. Therefore, in modern countries, CFCs and HCFCs are now phased-out and replaced by hydrofluorocarbons (HFCs) with zero ozone depletion potential (ODP) but non-zero global warming potential.

Advantageously, heat pump drying can be designed to operate with natural fluids contributing to significant drop in green house gas emission. These dryers operate in closed cycles both in the heat pump fluid and drying air loops. Then, this is green technology with no particles, fines or energy exhausted from the dryer.

Conventional dryer's limitations on low quality product, environment, energy and high cost can be solved by applying heat pump dryers that now are a ready-to-use technology. It operates in a range of temperature that can be set according to the thermal sensibility of the material and product. Combining low and medium temperatures in a unit heat pump dryer saves energy and enhances product quality (Alves-Filho, 2016).

Heat pump dryer recovers the energy usually lost in air exhaust in open common dryers. In a closed loop this dryer fully uses this energy, firstly, by condensing vapor and boiling the fluid in the evaporator and, secondly, by re-heating the drying air and condensing the fluid in the condenser. That is, the fluid flows through the evaporator where it absorbs latent heat from the changing phase exhaust vapor and recycles it to the condenser. Consequently, heat pump dryer is a green technology since it operates with natural fluid with zero global warming potential and zero ozone depletion potential.

2. Material and methods

2.1 Vapor compression heat pump drying

The dryers and devices described next were designed, built and tested at the Norwegian University of Science and Technology (NTNU). A common heat pump cycle is the single-stage vapor compression where an evaporator cools the moist air and condenses the vapor by capturing the corresponding latent heat of vapor condensation (Alves-Filho, 2016; Dossat, 1981).

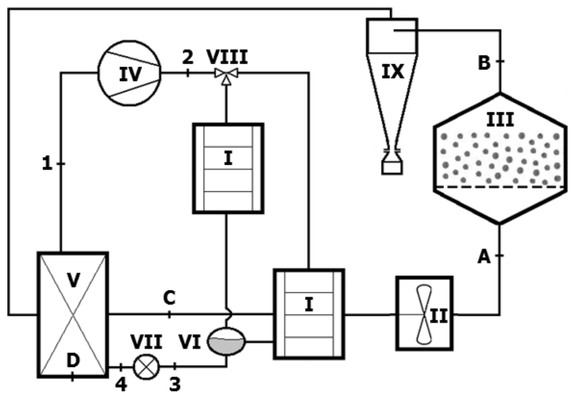

Figure 1: Heat pump fluidized bed drying: I – condensers (heaters), II – blower, III – fluidized bed drying chamber with onion flakes, IV – compressor, V – evaporator, VI – receiver, VII – throttling valve, VIII – three way valve, IX – cyclone, 1 – saturated vapor, 2 – superheated vapor, 3 – saturated liquid, 4 – vapor and liquid mixture, A – inlet of the drying chamber, B – outlet of the drying chamber, C – inlet of condenser, D – evaporator surface.

A vapor compression heat pump has a valve dividing low and high pressure sides and components shown in Figure 1. This is the layout of a pilot heat pump fluidized bed dryer used onion flakes. A typical application is drying of 5×5×8 mm flakes with a water removal rate of 30 kg/h. The drying chamber inlet air temperature and relative humidity are 40 °C and 20 % and the outlet air relative humidity is 70 %. The evaporating temperature is 7.78 °C, the condensing temperature is 45 °C and the isentropic and volumetric efficiencies are 0.6 and 0.7, respectively. Saturated vapor is compressed and saturated liquid is throttled adiabatically. The major

calculations and dimensioning to characterize performance of the dryer includes: determining the air state points in the cycle, the heat pump fluid properties and calculating work, volumetric flow rate, evaporating and condensing capacities, coefficient of performance (COP), specific moisture extraction ratio (SMER) and performances-energy utilization of the heat pump dryer (Alves-Filho and Mujumdar, 2005).
The analysis shows that this heat pump dryer uses 1 kWh to remove 2.76 kg of water. The COP indicates that the heat pump dryer uses only 27.2 % of the total energy required for heating and drying. The reason for the improved performance of the heat pump dryer is a full energy recovery from exhaust vapor and using it to reheat the drying air.

2.2 Two stage vapor compression heat pump drying

Multiple stage heat pump dryer replaces single stage that has limits on performance for operation with large evaporating and condensing temperature difference (Granryd et al., 2009). Two stage heat pump dryer is designed according to the layout shown in Figure 2 (Alves-Filho, 2016). The lay-out include processes and cycle of the two-stage heat pump system has an open flash intercooler supplying saturated vapor to the intermediate pressure compressors placed in parallel to each other. The flash intercooler purposes are to provide only saturated liquid to the throttling device for improving the cooling effect by and to supply only saturated vapor to the second stage compressor for enhanced efficiency. A beneficial consequence is reduction of the discharge temperature and compression losses by mixing the vapors discharged by the two compressors.

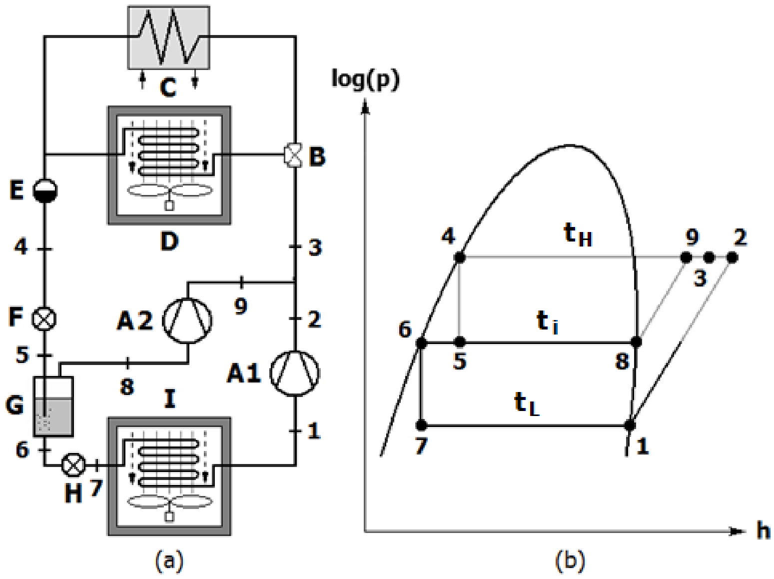

Figure 2: Two stage heat pump system with open flash intercooler and compressors in parallel. (a) The main components: A1 – low pressure compressor, A2 – intermediate pressure compressor, B – three-way valve, C – external condenser, D – drying channel with air heater, E – liquid receiver, F – intermediate pressure expansion valve, G – open flash intercooler, H – low pressure expansion valve, I – drying channel with air cooler; (b) Cycle with open intercooler and parallel compressors in the pressure – enthalpy diagram.

Figure 2a illustrates the layout of the components in the system with the drying channel. Figure 2b shows the heat pump cycle and processes in the pressure versus enthalpy diagram. The saturated vapor at point 1 enters the compressor A1 and it is discharged as superheated vapor at condensing pressure at point 2. Simultaneously, saturated vapor at point 8 enters the parallel compressor A2 and exits as superheated vapor at condensing pressure at point 9. The discharged vapors from points 9 and 2 are mixed and reach point 3. Then it flows into the three-way valve B, through the condensers C and D, changes phase to saturated liquid at point 4 and is collected into the liquid receiver E. The saturated liquid flows into the throttling device F, changes phase to a liquid-vapor mixture and is released into the flash intercooler G at point 5. From the bottom of the flash intercooler the saturated liquid at point 6 is throttled by the expansion valve H to become liquid-vapor mixture at evaporating pressure at point 7.

Then, the mixture flows through the evaporator I changing to saturated vapor at point 1 where it reenters the first stage compressor A1 once again. Concurrently, saturated vapor at point 8 and at intermediate pressure is available to enter once more the parallel compressor A2.
Thus, the processes in this heat pump cycle are:

- 1 to 2 is isentropic compression from evaporating to condensing pressure
- 3 to 4 isobaric condensation
- 4 to 5 is adiabatic expansion to intermediate pressure
- 6 to 7 is adiabatic expansion to evaporating pressure
- 7 to 1 is isobaric-isothermal evaporation
- 8 to 3 is isentropic compression.

Observe that the main purpose of the flash intercooler G is to separate the liquid and vapor phases and to assure that saturated vapor enters the suction line at point 8 and that only saturated liquid is available to enter the expansion valve H at point 6. The effect is an increased cooling effect from $h_1 – h_5$ to $h_1 – h_7$. Besides separation of liquid and vapor the other processes occurring in the intercooler and discharge of the two compressors are: isobaric mixing of discharged superheated vapors from 2 and 9 to reach point 3, isobaric-isothermal cooling from 5 to 6 and heating from 5 to 8.
Advantages of the two stages compression heat pump with flash intercooler and compressors in parallel are:

- reduction of the discharge temperature
- reduction of the compression energy loss and certainty that only saturated vapor at intermediate pressure occurs in point 8
- increasing of the cooling effect and the assurance that only saturated liquid at intermediate pressure enters the expansion device at point 6.

2.3 Method for selecting heat pump fluids

There are many fluids or refrigerants in the current market because ideal fluid that is flexible enough to fulfill satisfactorily all required operating conditions (Gosney, 1982). The selection of appropriate fluid depends on conditions in which compressors and other components operate safely and for long time. Therefore, selection involves relevant criteria for comparison of performances studying different fluids and properties in each state points of the heat pump cycle at different conditions. The recommend choice is fluid with reasonable cost, near zero ozone depletion potential and global warming potential, non-toxic and properties in accordance with actual operating conditions.
Selection is made based on cycles, conditions and environment and performance studies consider cycles with similar operating conditions. A heat pump operates in a cycle with a fluid that flows through the evaporator transferring energy from the heat source to the cooled medium and through the condenser rejecting energy from the fluid to the heat sink or heated medium. Mechanical vapor compression heat pump cycle is composed of processes such as evaporation, condensation, compression and throttling. The transfer of energy through these processes occurs in multiphase fluids and with phase changes and they flow through the heat exchangers and components exchanging energy and mass with the heat source and sink.
Depending on the critical point it would be desirable to select a fluid able to operate in transcritical cycle. The reason is improved performance compared to a subcritical cycle near the fluid's critical point. Condensation in subcritical cycle the occurs in the two-phase region and temperature near the critical point leading to sharp drop in the coefficient of performance. This problem is tackled by shifting condensation or gas cooling to the transcritical cycle. It happens above critical point and without phase change. As the condensation pressure approaches the critical point, the COP greatly increases by further gas cooling. For heat pump transcritical cycle, carbon dioxide or R744 is an excellent fluid because is critical temperature and pressure are 31.03 °C and 7,380 kPa, respectively. It is suitable for medium temperature drying and heat pump with R744 in a transcritical cycle has better performance compared to subcritical cycle.
Refrigerant is selected based on properties at the state points for evaporation and condensation. Condensing pressure and temperature depends on compressor discharge and the majority of compressors is manufactured with a maximum pressure of 25,000 kPa (currently increasing). Temperature and pressure are constant in the two-phase region for azeotropic mixtures and natural fluids while they vary for zeotropic blends and air. Natural fluids have a large variation of the saturation temperatures allowing a wide range of applications. The selection of the heat pump fluid can be based on environmental effects and health risks. Refrigerant selection for safety includes classes and groups according Standard 34 (Owen, 2009). Safety classes are indicated by: A: nontoxic for concentration below 400 ppm by volume, B: toxic at concentration above 400 ppm. Impact on climate change and environmental is minimized by using fluids with low global warming potential (GWP), which is indicator of heat trapped as greenhouse gases. GWP 0 is the current reference value for carbon dioxide.

3. Results and discussions

The selection of natural fluids, including ammonia and carbon dioxide, advanced materials, instruments and controls resulted in green heat pump dryers currently available at NTNU, which are discussed next.

3.1 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 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.

3.2 Heat pump tunnel dryer operating with natural ammonia refrigerant

Ammonia was selected as the natural fluid and used in the fluidized bed and tunnel drying technologies designed and built at NTNU.

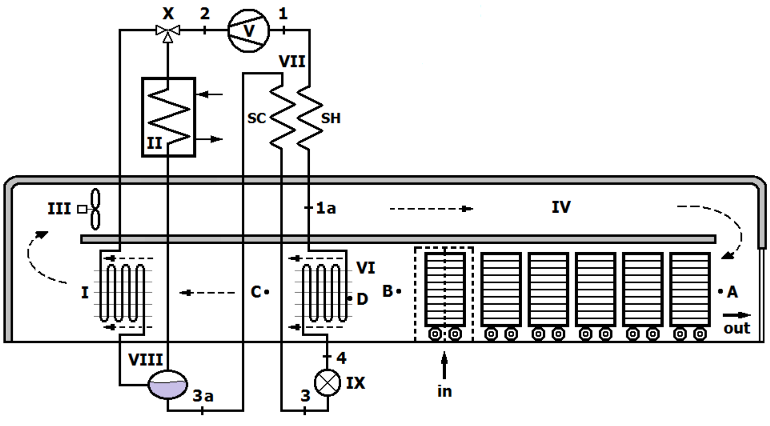

Figure 3: Heat pump tunnel dryer with natural fluid R717: I – internal condenser, II – external condenser, III – blower, IV – tunnel drying chamber with salted split cod, V –compressor, VI – evaporator, VII – internal heat exchanger, VIII – liquid receiver, IX – throttling valve, X – three way valve, 1a: saturated vapor, 1: superheated vapor at low pressure, 2: superheated vapor at high pressure, 3a: saturated liquid, 3: subcooled liquid, 4: vapor and liquid mixture, A – inlet of the drying chamber, B – inlet of the evaporator, C – inlet of condenser, D – evaporator surface SC – subcooled liquid, SH – superheated vapor, in – trolley with wet material inlet, out – trolley with dry product outlet.

The fluidized bed heat pump dryer 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.
The heat pump tunnel dryer shown in Figure 3 operates with natural ammonia refrigerant or R717 and it is used to dry salted and split cod fish. The drying chamber air temperature and relative humidity are 20 °C and 35 %

and the exhaust air is at 85 % relative humidity. The tunnel holds 6 trolleys each containing 400 kg of wet cod fish. The initial and final moisture contents are 80 %wb and 20 %wb, respectively. The dryer operates 20 hours per day and produces two trolleys of dried cod daily (simultaneously, two trolleys with wet fish are loaded in the dryer per day). The evaporating temperature is 2.5 °C and the condensing temperature is 35 °C. The isentropic and volumetric efficiencies are 0.65 and 0.75, respectively.
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.

4. Conclusions

HPD is a green technology with zero GWP and ODP when operating with natural fluids. This technology has been applied for drying foods and pharmaceuticals as porous solids or liquid phases as well as thermal sensitive materials. Properly 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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