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TWO STAGE HEAT PUMP DRYER**TECHNICAL FILED**

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This invention relates to a heat pump dryer, for example for drying of food or agricultural products. In particular the invention relates to a two-stage heat pump cycle
5 which advantageously provides better heat recovery and control of drying air.

BACKGROUND OF THE INVENTION

Commonly available heat pump dryers are single-staged. A single-staged heat pump has one evaporator. This evaporator has to undertake both the duties of sensible and latent heat absorption.

10 A two-stage heat pump has now been developed according to the invention incorporating a two-stage evaporation system where one evaporator operates at a higher pressure with respect to the other. Advantageously, a two-stage system enables the recovery of more latent energy from the drying air and flexibility to implement several control strategies for better humidity control. For many drying applications, in order to
15 reduce drying energy for product moisture removing and improve the product quality, both energy recovery and air conditioning play an important role in efficient drying.

In improving heat recovery, the high-pressure evaporator advantageously assumes part of the cooling duty. It has been found that this allows the low-pressure evaporator to dedicate more of its thermal capacity for dehumidification. For better humidity control, the
20 arrangement of evaporators in the air duct is advantageously such that it allows the air humidity to be controlled by two methods. One is to use an air bypass process through the evaporators to control the dehumidification. The other method involves the regulation of the mean coil surface temperature of the high-pressure evaporator for sensible and latent heat extraction.

25 Another development of the present system is the incorporation of an external evaporator to the dryer. The external evaporator plays a dual role. Its first role is to assist

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in the quick start-up of the heat pump dryer. This is accomplished by 'absorbing' sensible heat from the surroundings during the on-cycle process until the condenser reaches the right pressure level. Its second role is to serve as a 'dummy' load to inject auxiliary load to the refrigeration system when low latent load in the chamber is encountered. The external
5 evaporator advantageously ensures a consistent external load for heat recovery when the latent load in the drying chamber is low. This intervention is beneficial to drying processes where the initial latent load is high but diminishes progressively as drying proceeds into the falling rate region.

The present two-stage heat pump drying system advantageously also forms the
10 modular building block for designing advanced multi-stage heat pump dryers to meet demands for higher product quality and energy efficiency.

As such, the present invention advantageously provides better energy recovery by improving the latent to total heat recovery ratio, and better control of the drying air through better sensible and latent heat exchange through the evaporators and condensers. Further,
15 the invention advantageously provides a heat pump dryer that is equipped with a quick start-up mechanism as well as a drying system that ensures consistent load for heat recovery throughout the drying process, and an energy efficient two-stage field heat pump dryer that is easily integrated to any drying chamber.

SUMMARY OF INVENTION

20 According to the present invention there is provided a heat pump dryer assembly comprising:

a heat pump unit comprising (i) a two-stage internal evaporator system comprising high and low pressure evaporators for heat recovery and conditioning of drying air; (ii) a hot-gas condenser and sub-cooler arrangement for introducing sensible heat to said
25 drying air; and (iii) an economiser installed before and after said evaporators for precooling said drying air before it enters said evaporators and preheating said drying air before it enters said condenser;

a compressor;

an external evaporator for receiving said drying air from said hot-gas

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condenser and sub-cooler arrangement and for facilitating constant latent load maintenance;
a drying chamber having ports for introducing fresh air thereto and exhausting
drying air therefrom.

In order to facilitate easy scale-up of the drying chamber without the need for altering
5 the configuration of the heat pump unit, it is preferred that the heat pump unit and the drying
chamber be partitioned from each other. The configuration of the heat pump unit is
preferably such that the high pressure evaporator operates as a partial dry/wet coil, and the
low pressure evaporator operates as a dedicated wet coil. Furthermore, in a preferred
embodiment a back pressure regulating valve is installed at a discharge line of the high
10 pressure evaporator to ensure constant evaporating pressure.

In a preferred embodiment, the hot-gas condenser and sub-cooler arrangement
comprises a hot-gas condenser and two sub-coolers. Such an arrangement advantageously
provides the required sensible heat for the drying air to attain the desired temperature.
Preferably, the assembly further comprises control means for ensuring sufficient sensible heat
15 is provided from the hot gas condenser and sub-cooler arrangement to the drying air to
achieve a predetermined air temperature. Thus, the air temperature of the drying air may be
regulated as desired.

In order to regulate the temperature of the drying air, the assembly preferably
comprises a condenser, such as a air-cooled condenser, which facilitates a discharge of excess
20 heat from the drying air in the system. Furthermore, in a preferred embodiment the assembly
comprises a bypass damper system for regulating the flow of bypass air through the
assembly. More preferably, a further control means is provided for modulating the bypass
damper system to maintain a desired humidity of the drying air.

In order to cater to higher temperature requirements of the drying air, the assembly
25 may further comprise an auxiliary heater for facilitating the introduction of additional
sensible heat to the drying air. Preferably, a further control means is provided for activating
the auxiliary heater as required.

The heat pump dryer advantageously achieve maximum heat recovery for efficient
and economic drying of, for example industrial and agricultural products. This is achieved
30 using low and high pressure internal evaporators and an external evaporator for cooling and

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dehumidification of the drying medium. The exit air from the drying chamber is first passed through the high pressure evaporator to undergo pre-cooling process before the low pressure evaporator dehumidifies the air for latent heat recovery. The arrangement of the evaporators allows different percentage of air to bypass and be mixed downstream of the coils. This enables the humidity of the drying air to be controlled through a simultaneous process of dehumidification and mixing.

On the condenser side, two subcoolers are preferably used for heat recovery. The subcoolers ensure that for high temperature operations more heat from the evaporators is recovered by making available more heat transfer area between the air and the refrigerant.

The system further incorporates a passive evaporator-economiser for pre-cooling of the air before the evaporators and pre-heating before the condensers. The facility can also operate as a chiller unit thus enabling both cold and hot air drying to be performed.

In another aspect, the invention provides a heat pump dryer assembly comprising:

- a heat pump unit comprising a two-stage internal evaporator system comprising high and low pressure evaporators for heat recovery and conditioning of drying air;
- a compressor;
- an external evaporator for facilitating constant latent load maintenance;
- a drying chamber having ports for introducing fresh air thereto and exhausting drying air therefrom.

BRIEF DESCRIPTION OF THE DRAWINGS

A more detailed description of the invention will now be provided with reference to the drawings which illustrate embodiments of the invention and serve to explain the principles of the invention. It is to be understood, however, that the schematic drawings are designed for the purpose of illustration and explanation of the drying system, and not as a definition of the limits of the invention.

FIG. 1 is a frontal view of a prototype 2-stage heat pump dryer unit. As shown, the two evaporators, high and low pressure, are arranged in series. An economiser is arranged around these two evaporators for pre-cooling and pre-heating of the drying air.

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FIG. 2 is a schematic diagram showing the high and low pressure evaporator system.

FIG. 3 is a schematic showing a control mechanism for the external evaporator to enable quick system start-up and consistent latent load absorption.

5 FIG. 4 is a circuit diagram showing the connections for the condenser and subcoolers. The diagram shows the refrigerant flow from a 3-way modulating valve to the vapour chamber and air-cooled condenser.

FIG. 5 is a schematic diagram showing a control mechanism for shutting down the heat pump and maintaining the air temperature with an auxiliary heater bank.

10 DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

In the following sections, the details of the dryer design configuration, the refrigeration components of the two-stage heat pump cycle and the various control strategies to condition the humidity of the air will be presented. This is followed by the description of the system quick start-up mechanism and method for maintaining consistance
15 heat recovery throughout the drying process.

DRYER DESIGN

Figure 1 shows the two-stage heat pump dryer unit. It can be observed that the dryer has been designed such that the refrigerating components of the heat pump cycle are partitioned from the drying chamber. This design advantageously allows further scale up
20 of the drying chamber without changing the position of the coils and other refrigerating components. Further, such a design permits the construction of a field dryer where the refrigerating equipment can be readily integrated with any containerised chamber. This mode of construction allows flexibility for chamber scale-up as well as system maintenance.

25 HEAT PUMP COMPONENTS

A two-stage heat pump drying system has been designed to improve the heat

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recovery process and thus the thermal efficiency of the dryer. The basic principle in the heat recovery process is to improve the latent to total energy transfer at the evaporators. The following sections illustrate how the 2-stage system is able to improve heat recovery process.

5 *Internal evaporators (high and low pressure)*

Figure 2 shows the connections for the two internal evaporators. The present system uses two direct expansion internal evaporators to achieve the desired humidity of the air by expansion of the liquid refrigerant from the condenser to two different pressure levels. Two thermostatic expansion valves 5 and 6 are used to expand the refrigerant leaving the condenser to two different pressure levels. The use of two evaporators at different pressure levels advantageously improves the latent to total cooling energy transfer at the evaporators and enables better control of the drying air humidity. The drying air leaving the drying chamber is cooled to its dew point or below after the high-pressure evaporator. In this way, the high-pressure evaporator operates as a partial dry/wet coil while the low-pressure evaporator operates as a dedicated wet coil with more dehumidification capability. The use of direct expansion evaporator coils facilitates modulation of the refrigeration capacity when the latent load in the chamber varies. Figure 2 further shows how the back pressure regulating valve 1 is installed at the discharge line of the high pressure evaporator. This regulator ensures a constant evaporating pressure and thus a constant surface temperature on the evaporator coil. The regulation process is achieved by throttling in the compressor suction line 1a. The amount of refrigerant through the coil is matched with the evaporator load.

External evaporator

Figure 3 shows a control mechanism for the external evaporator. The external evaporator 14 plays a dual role. Its first role is to assist in the quick start-up of the heat pump dryer. This is accomplished by pressure switch 16 sending an on-off signal 17 to the normally closed solenoid valve 12 when compressor discharge pressure 20 reaches a pre-set value. This allows the flow of refrigerant to the thermostatic expansion valve 13 and external evaporator 14, resulting in heat being absorbed from the environment by the external evaporator 14. Another on-off signal is sent to the solenoid valve 12 when the

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compressor discharge pressure 20 reaches another pre-set value, terminating the refrigerant flow to the thermostatic expansion valve 13 and thus cutting off the external evaporator 14 operation.

The second role of the external evaporator 14 is to serve as a 'dummy' load to inject auxiliary sensible load to the refrigeration system when low latent load in the chamber is encountered. The external evaporator 14 ensures a consistent external latent load for heat recovery when the latent load in the drying chamber is low. This intervention is beneficial to drying processes where the initial latent load is high but diminishes progressively as drying proceeds into the second falling rate region. At the second falling rate period, a feedback signal 22 obtained from the weight of the product, a measure of the latent load in the chamber, is sent to the PID controller 19. If the weight of the product reduces to below a set value, the controller 19 sends an on-off signal 18 to the solenoid valve 12 and activates it. This action allows the refrigerant to flow to the thermostatic expansion valve 13 which in turn distributes the refrigerant to the external evaporator 14 based on the bulb temperature 15. This allows heat to be absorbed from the environment by the external evaporator. Under this condition, the amount of absorption of latent energy required to offset the latent losses in the chamber due to the product's falling rate can be determined and consistent latent absorption for the system can be maintained.

Condenser and subcoolers

Figure 4 shows the connections for the hot-gas condenser 24 and the two subcoolers 25 and 26. One hot gas condenser 24 plus two subcoolers 25 and 26 provide the required sensible heat for the air to attain a desired temperature. The two subcoolers 25 and 26 recover additional heat by making available more heat transfer area for the refrigerant to condense from vapour to liquid form. The use of two subcoolers 25 and 26 maximises the recovery process and improves overall energy efficiency.

Economiser

A refrigerant economiser is installed before and after the high and low pressure evaporator coils. The economiser undertakes part of the cooling duty for the evaporator and heating duty for the condenser. It pre-cools the air before it enters the evaporators and pre-heats the air before it enters the hot gas condenser. The use of the economiser to

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transfer heat from air on one side of the evaporator to the air on the other side can increase the water extraction capacity of the heat pump dryer. Pre-cooling at the air-on side of the evaporators enables the major part of the cooling coil capacity to be used to extract water from the air.

5 CONTROL OF DRYING AIR CONDITIONS

The desired drying air conditions are generated and controlled with the use of three PID controllers. One controller is used to provide sufficient sensible heat from the hot-gas condenser (HGC), and the two sub-coolers (SC1 and SC2) to the drying air to achieve the air temperature. The second controller is used to control sensible heat input from an auxiliary heater to cater to higher air temperature requirements. The third controller is used to modulate the face and bypass dampers of the evaporators so as to control the dehumidification process and maintain the desired humidity of the drying air.

Air temperature

Figure 4 shows a control mechanism to control the drying air temperature. The air temperature is controlled by sending a continuous PID signal to a 3-way modulating valve 23. This valve regulates the flow of refrigerant vapour to the HGC 24, SC1 25 and SC2 26, and bypassing the rest before the two lines 28a and 28b meet at point 28c. The mixed refrigerant then enters the air-cooled condenser 29. The air-cooled condenser 29 is used to reject the excess heat before the entering liquid receiver 30.

Figure 5 illustrates another control strategy to improve energy saving by using the auxiliary heaters 31 to provide the sensible heat for the drying air during the last stage of drying. Towards the last fraction of drying, approximately 10 to 20% of the drying process, the humidity of the air remains relatively the same. Only the drying air temperature drops because of the continuous provision of sensible heat to remove product moisture. Therefore, in an economical sense, switching the heat pump system off and providing continuous heating with the auxiliary heater bank 31 would reduce operating costs. To accomplish this, a feedback signal from the weighing machine 38 is fed to the PID controller 34, which in turn sends two simultaneous signals 35 and 35a to the compressor and the auxiliary heater bank respectively. Signal 35a activates the on-off relay 32 and closes the contact for the auxiliary bank while signal 35 de-activates the normally

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close on-off relay 36a. Once relay 36a is de-activated, the potential free contact 37 is opened. This causes the motor starter relay 36 to cut out the signal from the 3-phase power supply to the scroll compressor 33. This chain of events activates the heaters in the auxiliary heater bank 31 and de-activates the scroll compressor 33, resulting in the shut
5 down of the heat pump and controls the air temperature with the auxiliary heater bank 31.

Air humidity

The third PID controller is used to control the motorised damper. The damper regulates the flow of air through the face and bypass dampers of the evaporators. The dehumidified air through the evaporators is mixed with the bypassed air to maintain the
10 desired humidity of the air.

The second method of humidity control relies on a back pressure regulating valve 1 as shown in Figure 2, to regulate the operating pressure of the HP evaporator. The operating pressure of the HP evaporator serves as an accurate indication of the evaporator-coil temperature. On many air conditioning applications, the maintenance of a fixed coil
15 temperature is all that is required for accurate control of both sensible and latent heat removal. Through precise regulation of the back pressure regulator 1, the mean coil surface temperature is set to extract the required sensible and latent heat to obtain required air humidity.

Air flow rate

20 The flow rate of the drying air to the chamber is controlled by a 3-phase frequency inverter. By regulating the frequency of the inverter and reading from the air vane anemometer, the flow rate of the air entering the chamber can be set to the desired volumetric flow.

Refrigerant Circuit Control

25 To ensure that the scroll compressor works within the recommended operating envelope, the condensing temperature is set to operate in the range of 45°C to 55°C (16.5 bar to 21 bar, respectively, measured at the compressor discharge after de-superheating). The lower limit is proposed for an ambient temperature of 35°C and allowing a

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temperature difference of 10°C for sufficient heat rejection to the surroundings by the air-cooled condenser. The upper limit is obtained with the purpose of safeguarding the compressor life by preventing overheating of the motor. At the evaporator side, in order to achieve a cooling capacity of 14.2 kW, an SST of 5°C is normally set. A lower evaporating temperature can be set but there is always a possibility of the coil freezing up. At the same time, the corresponding cooling capacity would be reduced. The cut-in and cut-out pressure for the external evaporator is set at 14 bar and 16 bar, respectively, to achieve the desired condensing temperature and maintain the evaporator temperature within the operating range.

10 *Example*

Initial commissioning runs have been conducted to evaluate the system stability and time to approach steady-state conditions. Table 1 shows results obtained from air-side measurements without any latent load in the chamber. This example is for illustrative purposes only and should not be construed as limiting on the invention in any way.

Table 1 - Results obtained from heat pump system and air-side measurements

Compressor and heat pump system operating parameters:	
Compressor running ampere	8.5 Amp
Blower running ampere	3.2 Amp at 50 Hz
Suction Pressure	4.0 to 5.0 bar
Discharge Pressure	19 to 21 bar
Chamber temperature	50°C
Relative humidity	25%
Air flow speed	2.8m/s
Air-side temperature	
3-way temperature PID setting	48.5°C
After drying chamber	47.5°C
After pre-cool coil	44.0°C
After HP evaporator	22.5°C
After LP evaporator	13.5°C
After pre-heat	18.6°C
After SC2	32.0°C
After SC1	37.0°C
After HGC	48.3°C

Based on values in Table 1 and compressor energy consumption, the COP of the heat pump operating at 48.5°C is calculated to be 2.96. We expect a higher heat recovery and

5 improved COP when latent load is available in the chamber.

NOTATION

COP	Coefficient of performance	dimensionless
EC	Economiser	-
HGC	Hot gas condenser	-
HP	High pressure evaporator	-
LP	Low pressure evaporator	-
PID	Proportional-Integral-Differential	-
SC1	Subcooler 1	-
SC2	Subcooler 2	-
SDT	Saturation discharge temperature	°C
SMER	Specific moisture extraction rate	kg/kWh
SST	Saturation suction temperature	°C

CLAIMS

1. A heat pump dryer assembly comprising:

a heat pump unit comprising (i) a two-stage internal evaporator system comprising high and low pressure evaporators for heat recovery and conditioning of drying
5 air; (ii) a hot-gas condenser and sub-cooler arrangement for introducing sensible heat to said drying air; and (iii) an economiser installed before and after said evaporators for precooling said drying air before it enters said evaporators and preheating said drying air before it enters said condenser;

a compressor;

10 an external evaporator for receiving said drying air from said hot-gas condenser and sub-cooler arrangement and for facilitating constant latent load maintenance;

a drying chamber having ports for introducing fresh air thereto and exhausting drying air therefrom.

2. An assembly according to claim 1, wherein said heat pump unit and said drying
15 chamber are partitioned from each other to facilitate scale-up of said drying chamber without altering said heat pump unit.

3. An assembly according to claim 1, wherein said high pressure evaporator operates as a partial dry/wet coil, and said low pressure evaporator operates as a dedicated wet coil.

4. An assembly according to claim 1, wherein a back pressure regulating valve is
20 installed at a discharge line of said high pressure evaporator to ensure constant evaporating pressure.

5. An assembly according to claim 1, wherein said hot-gas condenser and sub-cooler arrangement comprises a hot-gas condenser and two sub-coolers.

6. An assembly according to claim 1, comprising control means for ensuring sufficient
25 sensible heat is provided from the hot-gas condenser and sub-cooler arrangement to the drying air to achieve a predetermined air temperature.

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7. An assembly according to claim 1, comprising a condenser for regulating temperature of said drying air by discharging excess heat from said drying air.
8. An assembly according to claim 7, wherein said condenser is an air-cooled condenser.
9. An assembly according to claim 7, wherein said condenser is one which can reject
5 heat by heat transfer through cooling media besides air, such as a water-cooled condenser.
- 10 An assembly according to claim 1, comprising a bypass damper system for regulating the flow of bypass air through the assembly.
- 11 An assembly according to claim 8, comprising control means for modulating said bypass damper system to maintain a desired humidity of the drying air.
- 10 12 An assembly according to claim 1, comprising an auxiliary heater for facilitating the introduction of additional sensible heat to cater to higher temperature requirements of said drying air.
- 13 An assembly according to claim 12, comprising control means for activating said auxiliary heater as required.
- 15 14 An assembly according to claim 1, wherein said economiser comprises two plate-fin coils charged with refrigerant.
- 15 An assembly according to claim 1, wherein said economiser comprises a compact heat exchanger or fin-tube heat exchanger.
- 16 An assembly according to claim 1, wherein said compressor is a scroll-type
20 compressor.
- 17 An assembly according to claim 1, wherein the compression of the vapour refrigerant takes place with compressors operating with different compression methods such as centrifugal, reciprocating, rotary and screw compressors.

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18 An assembly according to claim 1, wherein the compressor can be open, semi-hermetic or fully-hermetic.

19 A heat pump dryer assembly comprising:

 a heat pump unit comprising a two-stage internal evaporator system comprising

5 high and low pressure evaporators for heat recovery and conditioning of drying air;

 a compressor;

 an external evaporator for facilitating constant latent load maintenance;

 a drying chamber having ports for introducing fresh air thereto and exhausting drying air therein.