A THEOREITICAL ANALYSIS OF THE APPLICATION OF CO_2 THANSCRITICAL HEAT PUMP TO THE DRYING OF SEEDS

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ABSTRACT

A new heat pump drying method of applying CO_2 transcritical process to the drying of biotechnology materials (seeds) is originally proposed in the paper. The method makes full use of the advantage of heat recovery in the cycle, and heat rejection process has a good temperature matching with drying medium (air). The paper presents a contrastive analysis of the coefficient of performance (COP) and the specific moisture extraction rate (SMER) of drying heat pump with CO_2 and that with conventional working fluids R134a, NH_3 and R12 under the same drying conditions. The results show that heat pump drying with CO_2 transcritical process is superior to that with conventional working fluids, and is an environment-protecting, energy-saving and highly efficient method of drying seeds.

1. INTRODUCTION

Scientists worldwide are being engaged in searching for refrigerant alternatives, as CFCs and HCFCs, widely used in refrigeration and heat pump industry, have a greenhouse effect and do harm to the ozone layer. Thus, looking for the efficient and pollution-free working fluids becomes an international hot topic. Since 1990s, research in the use of CO_2, a natural refrigerant, in replacement of man-made working fluids has been given special attention, and researchers in Norway, Germany, Denmark have made many achievements (Lorentzen G. 1994) (Pettersen J. et al. 1995). CO_2, whose ODP=0, GWP=1, is of great significance to environment protection. Moreover, it comes from industrial waste gases, and is nonflammable. For these reasons, it has obvious advantages in term of economy, safety, and environment protection. Consequently, CO_2 is more and more widely used as a working fluid in refrigeration, air condition and heating system. Heat pump drying is one of these uses.

Heat pump drying can freely control the temperature of drying medium. The heat pump dryer (HPD) is, therefore, suitable for biotechnological materials, especially for the drying of seeds. The drying of seeds is different from that of grains, fruits, vegetables and other crops in that seeds are more sensitive to the temperature and humidity of the drying atmosphere. The process should take into account the distinct shape and inner structure of seeds; otherwise, improper drying will result in seed deterioration (Jialing T. and Guanghua Z. 1991). To ensure the seed vigor, keep their biological features and hereditary characteristics, and achieve the aim of environment protection and energy saving, CO_2 transcritical heat pump drying is an ideal drying method. This paper originally presents the feasibility of using CO_2 as a refrigerant in the drying of seeds. The heat rejection process in the cycle can have a good temperature matching with drying medium (air), which leads to the result that the COP of the system is over 6.0. So this HPD has good potentials in practical uses.

2. AN ANALYSIS OF THE THERMODYNAMIC BEHAVIOUR OF CO_2 TRANSCRITICAL CYCLE

The critical temperature of CO_2 is low, only 31.1°C; its critical pressure is 7.38MPa. When used as a working fluid in vapor compression refrigeration cycle, the COP and refrigeration capacity are under a direct influence of the temperature of the cooling medium and that of the ambience. If the transcritical cycle is used, their influence can be avoided. From the h-s diagram and lgP-h diagram of the CO_2 transcritical cycle (Lorentzen G. 1994), we can see that heat absorption and rejection of the cycle occur in subcritical and supercritical areas respectively. Moreover, the heat rejection process is one of temperature change, which means it has a great temperature glide. This temperature glide, matching the heat resource of variable temperature needed, is a special Lorenz cycle, and, when used in heat recovery, has a high efficiency. This is one of its advantages.

Another advantage is that under supercritical pressure, CO_2 has no saturated state, and its temperature and pressure is independent. When the evaporation temperature and outlet temperature of the gas cooler remain unchanged, with the change of the heat rejection pressure, the COP of the cycle has a maximum (whose corresponding pressure is called optimal heat rejection pressure), thus economizing compressor work. Furthermore, as it has the inherent properties of a supercritical fluid, CO_2 has better heat transfer characteristics and less flow resistance than CFC. As it is less viscosity, we can promote heat transfer rate by increasing the flowing speed, and the volume of the whole equipment will be greatly reduced.

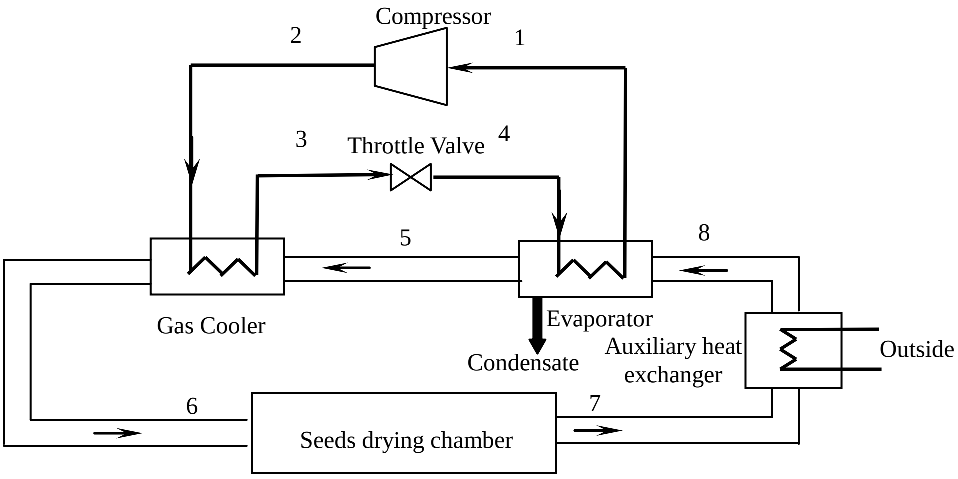

Figure 1. The Flow Chart of Closed Heat Pump Drying System with Auxiliary Heat Exchanger Applying CO_2 Transcritical Cycle.

3. PRINCIPLES AND FEATURES OF A CO_2 TRANSCRITICAL DRYING HEAT PUMP

3.1 A brief introduction to the process

Drying heat pump cycle, according to the cycle of the drying medium, can be further divided into the open system, the partially closed system and completed closed system. For the drying of organic substances such as seeds or wood, closed-loop process is usually used. For one thing, it has little interference from the ambience and has a wide scope of application; for another, because of the recycle of the drying medium (air), dehumidification can be achieved by evaporator, so that heat can be recovered, thus economizing energy. Ruiter (Ruiter J. P. et al. 1978) analyses several drying heat pumps, and the result of his experiments shows that the closed system can save energy by 40%, compared with the open electric heating system. Gopalnarayanan (Gopalnarayanan S., Radermacher R. 1997) believe that adding an auxiliary heat exchanger in front of the entrance of the evaporator can ensure a complete use of the latent heat of the refrigerant in condensing the steam in the humid air, which can improve dehumidification efficiency. This completely closed system with auxiliary heat exchanger is used in my research, and its flow chart can be seen from figure 1.

This system includes an inner cycle and an outer one. The former is the cycle of the refrigerant in the heat pump, and the latter, that of the drying air in the passage. The cycle of the refrigerant differs from conventional cycle in that the heat rejection device is a gas cooler instead of a condenser, and the refrigerant undergoes a continuous change of temperature, but have not phase change. As for the air cycle, its state changes are shown in figure 2. The air of low temperature and low humidity from the evaporator is heated in the gas cooler, enters the seeds-drying chamber, then, after a humidity exchange with seeds, the exhaust from drying chamber re-enters the evaporator to be dehumidified and recycled. The auxiliary heat exchanger in front of the entrance of the evaporator can reject the heat of the dried air into the ambience, and improve dehumidification efficiency.

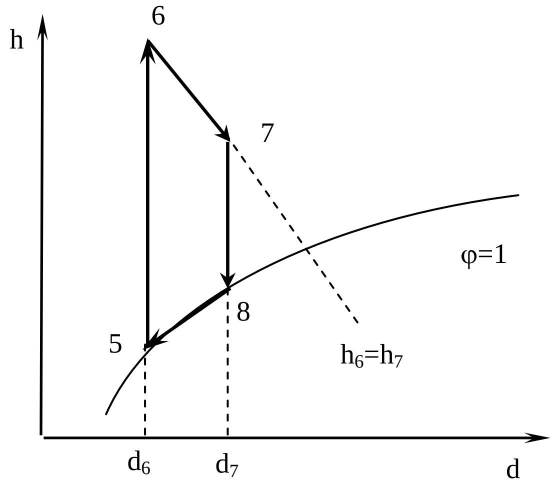

Figure 2. Enthalpy-Water Content Diagram of Air Cycle

3.2 The drying conditions of seeds

The equilibrated water content of seeds is mainly decided by the relative humidity of the drying atmosphere. For the dryer, which cannot do dehumidification, the relative humidity can only be reduced by raising the temperature. However, a high temperature will cause thermal denature of protein, and reduce vigor of seeds. If a HPD is used, dehumidification occurs in the evaporator, so the air of low temperature and low humidity can be used in drying without doing harm to seeds. The drying temperature of open-field crops’ seeds is usually lower than 50°C, and the relative humidity of the drying atmosphere, considering the equilibrated water content, should be about 17%. So, based on these conditions, and supposing the humidity of the exhaust from the drying chamber to be 55%, the state variables of the air at significant points in the drying process, given in table 1, are determined according to the figure 2. The property values of humid air and refrigerant are found from EES (Klein, S. and Alvarado, F. 1996). The exhaust temperature from the drying chamber is 34.7°C by calculation, which satisfied the requirements of heat rejection into the ambience.

Table 1. Thermodynamic Parameters of Humid Air at Significant Points in The Drying Process （Ambient pressure is 100kPa）

Value State	T [°C]	φ [%]	d [g/kg air]	h [kJ/kg]	s [kJ/kg·K]
5	18.300	0.998	13.338	52.177	5.795
6	50.000	0.170	13.338	84.764	5.901
7	34.662	0.550	19.487	84.764	5.905
8	28.000	0.803	19.487	77.841	5.882

4. A COMPARISION OF DRYING EFFICIENCY BETWEEN CO_2 AND CONVENTIONAL REFRIGERATIONS

The specific temperature of the refrigerant cycle is determined according to the property values of the drying air, calculated in the above part of this paper. Suppose the temperature difference of the pinch point between air and refrigerant to be 5°C, and the working fluid in the evaporator to have a superheating of 5°C, the performance and the drying effect of two systems are compared.

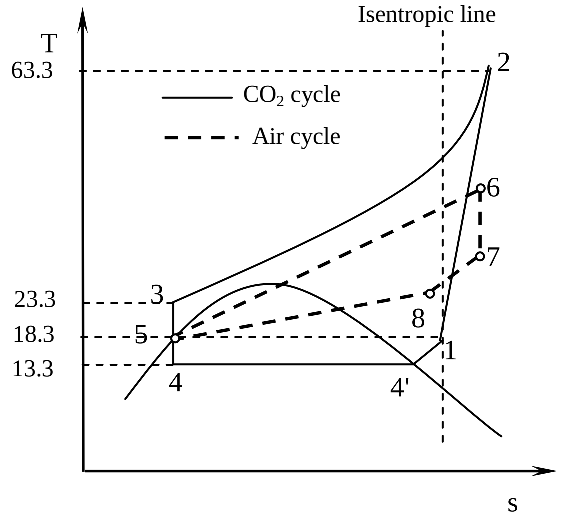

Figure 3 . T—S Diagram of CO_2 Trans-critical Drying Process.

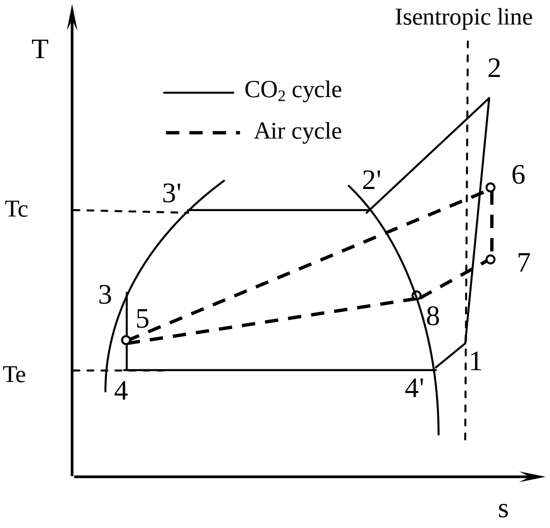

Figure 4. T—S Diagram of Subcritical Cycle of Conventional Working Fluids Heat Pump Drying Process.

4.1 The transcritical CO_2 drying process

The T-s diagram of the CO_2 drying system is shown in Figure 4. The process 1-2 is the irreversible compression in the compressor; process 2-3, supercritical isobaric cooling of CO_2 in gas cooler, which is interrelated with 5-6, the iso-humid heating process of the air. The process 3-4, throttling in the throttling valve; the process 4-1, evaporation of CO_2 in evaporator, which is interrelated with the process 8-5, the cooling and dehumidification of the drying air; process 6-7, isoenthalpic humidification in the seeds-drying chamber; process 7-8, heat rejection to the ambience by auxiliary heat exchanger. The isentropic efficiency of the compressor is supposed to be 0.75, and the ambient pressure is 100 kPa. In calculation, the influence of both the optimal heat rejection pressure of the CO_2 transcritical cycle and the temperature difference of the pinch point in the heat exchanger is taken into account. The thermodynamic parameters of the CO_2 cycle at the significant points are shown in table 2.

Table 2. Thermodynamic Parameters of CO_2 Transcritical Cycle

Value State	T [°C]	p [kPa]	h [kJ/kg]	s [kJ/kg·K]
1	18.300	4878.381	319.933	1.143886
2	63.348	8400.792	347.166	1.164221
3	23.300	8400.792	159.867	0.567099
4	13.300	4878.381	159.867	0.585464
4'	13.300	4878.381	308.075	1.102834

4.2 The subcritical drying process of conventional working fluids

Analyzing the working fluids R134a, NH_3, and R12 in the subcritical cycle, one can find that they differ from the CO_2 transcritical cycle in that their heat rejection process includes the deheating process 2-2’, the isothermal condensation 2’-3’ and the subcooling process 3’-3. The isentropic efficiency of the compressor remains 0.75 (in fact, as the pressure ratio of conventional working fluids is higher than that of CO_2, its isentropic efficiency is lower than CO_2 transcritical cycle). Table 3~5 are respectively thermodynamic parameters of R134a, NH_3, and R12 cycle.

Table 3. Thermodynamic Parameters of R134a Subcritical Cycle

Value State	T [°C]	p [kPa]	h [kJ/kg]	s [kJ/kg·K]
1	18.300	462.681	258.748	0.926027
2	70.218	1491.278	291.813	0.950342
2'	55.000	1491.278	272.687	0.893349
3'	55.000	1491.278	127.999	0.452445
3	23.300	1491.278	80.950	0.304201
4	13.300	462.681	80.950	0.305507
4'	13.300	462.681	253.896	0.909235

Table 4. Thermodynamic Parameters of NH_3 Subcritical Cycle

Value State	T [°C]	p [kPa]	h [kJ/kg]	s [kJ/kg·K]
1	18.300	690.329	1471.978	5.222869
2	131.887	2313.089	1712.246	5.375283
2'	55.000	2313.089	1474.536	4.720791
3'	55.000	2313.089	451.449	1.603175
3	23.300	2313.089	292.386	1.101105
4	13.300	690.329	292.386	1.105497
4'	13.300	690.329	1458.311	5.175572

Table 5. Thermodynamic Parameters of R12 Subcritical Cycle

Value State	T [°C]	p [kPa]	h [kJ/kg]	s [kJ/kg·K]
1	18.300	467.144	196.522	0.702652
2	72.597	1365.694	222.587	0.721720
2'	55.000	1365.694	207.919	0.678167
3'	55.000	1365.694	90.269	0.319655
3	23.300	1365.694	58.049	0.218397
4	13.300	467.144	58.049	0.219366
4'	13.300	467.144	193.093	0.690784

4.3 Analysis of the results

There are mainly two criterions to evaluate a HPD: COP, the performance of the heat pump cycle, and SMER, the moisture extraction efficiency of the HPD, whose definitions are:

$$COP = \frac{h[2]-h[3]}{h[2]-h[1]} \tag{1}$$

$$SMER = \left(\frac{m_A}{m_R}\cdot\right)_{cd} \frac{d[7]-d[6]}{h[2]-h[1]} \tag{2}$$

Where m_A and m_R are respectively the mass flow rate of air and refrigerants. According to the equation of heat equilibration:

$$m_A(h[6]-g[5]) = m_R(h[2]-h[3])$$

we obtain:

$$\left(\frac{m_A}{m_R}\right)_{cd} = \frac{h[2]-h[3]}{h[6]-h[5]} \tag{3}$$

Similarly,

$$\left(\frac{m_A}{m_R}\right)_e = \frac{h[1]-h[4]}{h[8]-h[5]} \qquad (3')$$

The subscripts of “cd” and “e” represent condensation and evaporation, respectively. Due to calculation error, there is a slight difference between these two numbers, and the value of the condensation is adopted in this paper. The results of the calculation are shown in table 6.

Table 6. Comparison of Performance and drying Effect Between HPDS Applying CO_2 and Conventional Working Fluids.

	CO_2	R134a	NH_3	R12
m_A/m_R	5.748	6.471	43.571	5.049
COP	6.878	6.377	5.909	6.313
SMER	4.672	4.332	4.014	4.288

From this table we can see that CO_2 transcritical HPD is superior to conventional working fluids subcritical HPD in both the performance of the heat pump and drying efficiency. If the difference of the isentropic efficiency is taken into account, its advantages in energy saving are even more obvious.

The main disadvantage of CO_2 transcritical drying heat pump is that the working pressure is high, which raises higher requirements for the sealing of the system and manufacture technology of its parts. Moreover, the compressor and the heat exchanger have to be re-designed to ensure the safety and reliability of the system. Fortunately, all these problems have a good solution now: the prototypes of CO_2 transcritical heat pump have come into being in Germany. In China, the first transcritical water-water heat pump, made by Institute of Thermal Energy of Tianjin University, has been successfully experimented on, which paves the way for future application and research.

5. CONCLUTIONS

1) CO_2 is an environment-protecting working fluid, whose ODP=0, GWP=1, and which can be obtained from industrial waste gases, so it has obvious advantages in term of environment protection and economy.
2) The analysis shows that CO_2 drying heat pump meets the requirements of drying seed.
3) CO_2 HPD uses transcritical heat rejection process instead of latent heat exchange, which makes the heat transfer process have a good temperature matching with drying medium, and leads a high heat transfer rate.
4) CO_2 HPD has an obvious effect in energy saving: COP is as high as 6.878, higher than that of the conventional working fluids R134a, NH_3, and R12 HPD.
5) CO_2 drying heat pump can increase the dehumidification efficiency of the drying system, and the SMER of the drying seeds, is higher than that of conventional refrigerants.

NOMENCLATURE

COP	coefficient of performance	p	pressure (kPa)
d	water content (kg/kg air, g/kg air)	SMER	specific moisture extraction rate (kg/kWh)
h	specific enthalpy (kJ/kg)	s	specific entropy (kJ/kg·K)
m_A	mass flow rate of air (kg/h)	T	Temperature (K)
m_R	mass flow rate of refrigerant (kg/h)	φ	Relative humidity(%)

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