Study on energy-saving performance of a transcritical CO_2 heat pump for food thermal process applications

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Abstract. In food processing, there are significant simultaneous demands of cooling, warm water and hot water. Most of the heated water is used only once rather than recycled. Current heating and cooling systems consume much energy and emit lots of greenhouse gases. In order to reduce energy consumption and greenhouse gases emission, a transcritical CO_2 heat pump system is proposed that can supply not only cooling, but also warm water and hot water simultaneously to meet the thermal demands of food processing. Because the inlet water temperature from environment varies through a year, the energy-saving performance for different seasons is simulated. The results showed that the potential primary energy saving rate of the proposed CO_2 heat pump is 50% to 60% during a year.

1. Introduction

The food processing industry is one of the energy-intensive industries. Energy efficiency, environmental protection, and food processing waste management have attracted increasing attention in the food industry. Typical utilities for operations in food processing plants consist of thermal energy, electrical energy, and water. For current heating and cooling systems, the thermal energy is supplied mainly by using fossil fuel boilers, which is the dominant source of energy in food processing. 37% of fossil fuels burned in the United States are used to generate steam in general. In the food industry, about 57% of fossil fuel consumption is to generate steam [1]. Boilers are designed to transfer heat from a combustion process to steam or hot water, and steam or hot water is used to provide process heat for washing, blanching, concentration, pasteurization, CIP (Cleaning-in-Place), and other processes. Approximately 25% of the electricity in the food industry is used for process cooling and refrigeration. Washing and blanching can be found in nearly every type of fruit and vegetable processing facility in the United States. Washing is often done using approximately 60℃ water, which aids in contaminant removal, and may involve the use of detergents. Water blanching is performed in hot water at temperatures ranging typically from 70℃ to 100℃ [2-3]. Major end use of electricity in food processing is refrigeration, which is used for process cooling, raw materials and product cold storage, and freezing applications, as well as building heating, ventilation, and air conditioning (HVAC) systems. After blanching or pasteurization, the foods are quickly subjected to cooling in order to prevent overcooking. Cold storage involves the storage of products in refrigerated rooms and can be used at several stages of food processing.

In general, in food processing, most of the required cooling temperature range is 0℃-15℃ while the required heating temperature range is 25℃-95℃ [4-6]. Most of the heated water is used only once and then drained. Typically, the heated water comes from environment and is not recycled. For

subcritical cycle heat pumps using HFC refrigerants, it is difficult to produce more than 80℃ hot water due to the limitations of the critical temperature. However, for transcritical CO_2 cycle heat pumps, the cooling process in the supercritical region is a temperature-changing process, which is particularly suitable for high temperature water production. Therefore, the transcritical CO_2 heat pump is more efficient and suitable than subcritical heat pumps to meet the heating requirements of temperatures up to 100℃. There were many literatures about transcritical CO_2 heat pump system [7-11], but the analysis about seasonal energy saving in food processing industry has not been reported to date.

In this paper, a transcritical CO_2 heat pump system is proposed for food processing. It can meet the heating and cooling requirements simultaneously. The characteristics and energy-saving performance are simulated and analyzed.

2. Methodologies

Figure 1 shows the current heating and cooling systems for food processing. Heating is supplied with natural gas or coal-fired boilers, and cooling is supplied with electrically driven ammonia refrigeration systems. These systems consume significant amounts of energy and emit large amounts of greenhouse gases. According to the requirements of simultaneous heating and cooling, a transcritical CO_2 heat pump system is proposed. Figure 2 shows the proposed system schematic of the CO_2 heat pump and figure 3 shows its cycle in a pressure-enthalpy diagram and temperature-entropy diagram. The CO_2 heat pump has the following distinctive features:

(1) Two gas coolers and one internal heat exchanger are involved in the cycle.

(2) Cooling media (-2℃ or lower), warm water (25℃-70℃), and hot water (75℃-100℃) can be supplied with one CO2 heat pump system simultaneously.

(3 Hot water temperature can be heated to as high as 100℃.

The internal heat exchanger is used to improve the $COP_{(cooling)}$ and the $COP_{(hot\ water)}$. The gas cooler II is used to heat warm water. Part of the warm water is further heated through the gas cooler I to be hot water.
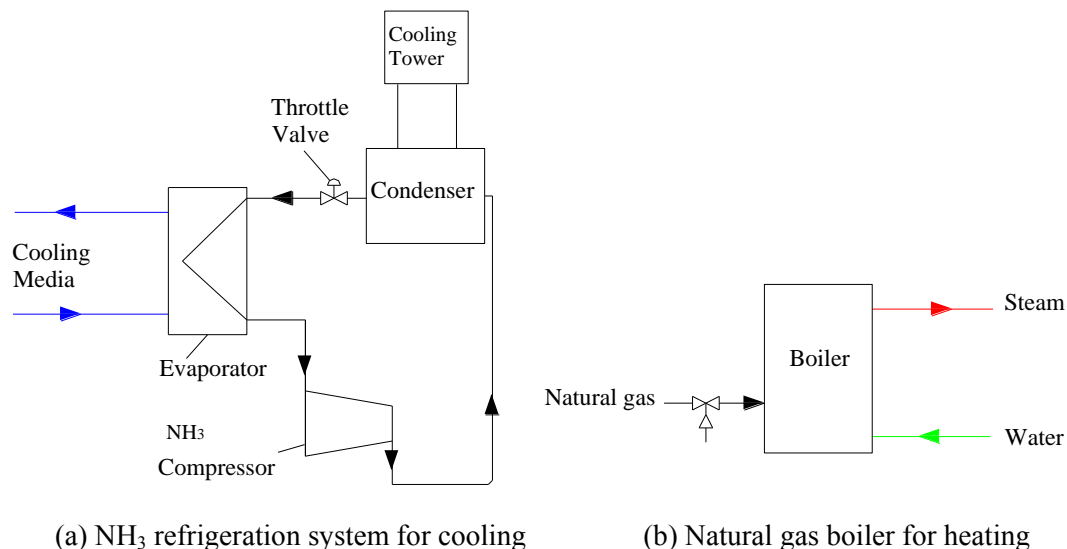

(a) NH₃ refrigeration system for cooling   (b) Natural gas boiler for heating

Figure 1. Current heating and cooling system for food processing.
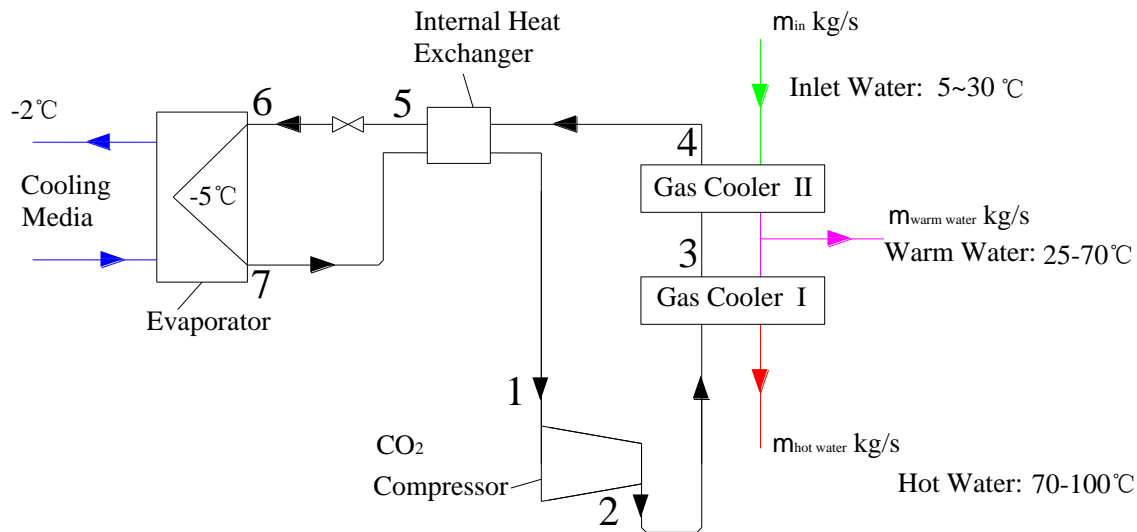
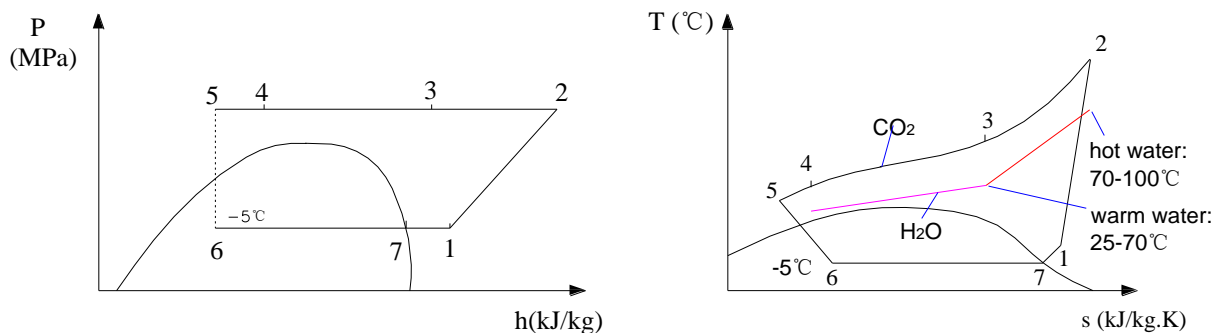**Figure 2.** Proposed system schematic of CO_2 heat pump for food processing.

Figure 3. Cycle plots of proposed CO_2 heat pump on P-h and T-s diagrams.

3. Performance simulation of the CO_2 heat pump system

3.1. Analysis of the Optimal COPs

The COPs are defined by the following equations:

$$COP_{(cooling)} = (h_7 - h_6)/(h_2 - h_1) \tag{1}$$
$$COP_{(hot\ water)} = (h_2 - h_3)/(h_2 - h_1) \tag{2}$$
$$COP_{(warm\ water)} = (h_3 - h_4)/(h_2 - h_1) \tag{3}$$
$$COP_{(system)} = COP_{(cooling)} + COP_{(warm\ water)} + COP_{(hot\ water)} \tag{4}$$

All simulation data reported in this paper were processed based on the data for physical property of CO_2 provided by the NIST Refrigerants Database REFPROP 8.0, and the performance of CO2 heat pumps are simulated by the software EES(Engineering Equations Solver) 2016. For the transcritical CO2 heat pump, when the cycle runs at optimal discharge pressure, the COP is maximal, and the cycle is defined as the optimal cycle.

Based on the COPs and the limitations of the discharge pressure and discharge temperature ($P \leqq$ 12MPa, $T \leqq 120℃$) , the optimal cycles are as the following:

(1) For Summer case (inlet water is 30℃), p = 9MPa, COP(cooling) = 2.16, COP(warm water) = 2.08, COP(hot water) = 1.08, COP(system) = 5.32.

(2) For Spring or Fall case (inlet water is 20℃), p = 9MPa, COP(cooling)= 2.65, COP(warm water)= 2.72, COP(hot water)=0.93, COP(system) = 6.3.

(3) For Winter case (inlet water is 5℃), p= 10MPa, COP(cooling)= 2.91, COP(warm water)= 2.98,COP(hot water)= 0.93, COP(system) = 6.82.

The following analysis is based on the assumption that the CO_2 heat pump operates at the optimal cycles.

3.2. Analysis of potential primary energy-saving rate

The following assumptions are made to predict the potential primary energy-saving rate:

(1) The fuel-to-steam efficiency of the natural gas boiler is 0.8 (usual range: 0.60-0.85), and the cooling capacity is 1000 kW.

(2) The heating value of natural gas from combustion is 35.3357 MJ/m^3.

(3) Natural gas power generation efficiency is 0.32.

(4) Isentropic efficiency of the compressor η is 0.7.

(5) Current system means that the heating is supplied with a natural gas boiler, and the cooling is supplied with R717 refrigeration system with $COP_{(cooling)}$ equal to 3.0.

Table 1. The potential primary energy-saving rate of the proposed CO_2 heat pump.

NO.		1.(summer)		2.(Spring or Fall)		3.(Winter)	
System type		Current system	Heat pump	Current system	Heat pump	Current system	Heat pump
Cooling capacity	kW	1000		1000		1000	
Cooling Refrigerant		NH_3	CO_2	NH_3	CO_2	NH_3	CO_2
COP		3	2.16	3	2.65	3	2.91
Power	kW	333.3	463.0	333.3	377.4	333.3	343.6
Natural gas	m^3/s	0.029	0.041	0.029	0.033	0.029	0.030
Heating capacity	kW	1463		1377		1344	
Heating Heat source		Boiler	Gas coolers	Boiler	Gas coolers	Boiler	Gas coolers
Efficiency/COP		0.8	3.16	0.8	3.65	0.8	3.91
Natural gas	m^3/s	0.052	0	0.049	0	0.048	0
Comparison on primary energy consumption Total natural gas consumption	m^3/s	0.081	0.041	0.078	0.033	0.077	0.030
Energy saving	%	—	50	—	57	—	60

The required cooling capacity is supposed to be 1000 kW, which does not affect the value of the potential primary energy-saving rate. Based on the assumption that the entire cooling capacity and heating capacity produced by the CO_2 heat pump are fully utilized, the predicted results of the potential primary energy-saving rates are shown in table 1.

It can be found that the potential primary energy-saving rate of the CO2 heat pump ranges from 50% to 60% during a year even though the COP of the CO2 heat pump is lower than that of the R717 refrigeration system.. This is due to the fact that all of the hot water and warm water produced by the CO2 heat pump is utilized for heating applications. In comparison, in the current heating system, there is a need of vast natural gas to heat water.

4. Conclusions
In order to reduce the energy consumption and greenhouse gas emissions in food processing, a transcritical CO_2 heat pump is proposed and introduced. The performance and primary energy-saving rate of the CO_2 heat pump are simulated and analysed. The proposed CO_2 heat pump can supply cooling (chilled brine solution at -2℃ or lower) and heating (warm water at 25℃-70℃, and hot water at 75℃-100℃) simultaneously during a year. The 100℃ hot water can be produced even in Winter. The warm water temperature and hot water temperature can be controlled to specific values as desired for a given application. Therefore, the proposed heat pump can meet not only the requirement of cooling, but also the requirement of different temperature water heating in process for food processing. Compared to the current heating and cooling systems, the primary energy-saving rates are predicted.

When the inlet water temperature of the gas cooler changes from 5℃ to 30℃ during a year, and all cooling capacity and heating capacity produced by the CO_2 heat pump are fully utilized, the potential primary energy-saving rate of the CO_2 heat pump is 50%-60% as compared with that of current heating and cooling systems. The system COP ranges from 5.32 to 6.82.

Based on the requirements of different kinds of food processing, the CO_2 heat pump parameters can be optimized, such as discharge pressure, suction temperature, outlet temperature of two gas coolers, warm water and hot water mass flow rates.

The proposed CO2 heat pump can be used in food processing, such as brewing, vegetable and fruit processing, animal slaughtering and processing. It also can be used in other industrial and commercial applications which demand cooling and heating simultaneously.

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