2014

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Study on Energy-Saving Performance of a Novel CO_2 Heat Pump with Applications in Dairy Processes

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ABSTRACT

In dairy processes, there are significant simultaneous heating and cooling demands. A novel type of transcritical CO_2 heat pump system is proposed, and its features and benefits are introduced. Based on the technical characteristics, primary energy-savings, and operating cost aspects, the CO_2 heat pump system is simulated and compared to current heating and cooling systems used in dairy plants. The results show that the highest primary energy-saving rate of the CO_2 heat pump is 51.5%. For fluid milk and cheese manufacturing processes, the primary energy-saving is 36.2% and 45.1%, respectively. In addition, the operating cost savings of fluid milk and cheese production are evaluated based on the cost structures in the states of Wisconsin, California and New York.

1. INTRODUCTION

The United States is the largest producer of cow's milk in the world. The dairy processing industry in the United States—defined as facilities engaged in the conversion of raw milk into consumable dairy products—is an important industry from both an economic and energy use perspective. The dairy processing industry generated just over $90 billion in product shipments, accounting for approximately 15% of the entire U.S. food industry’s economic output. As shown in Figure 1 (Adrian et al, 2011), on a product weight basis, the production of all subsectors of the dairy industry has grown from 1997 to 2009, except for the ice cream and frozen dessert subsector. The subsector with the highest production was fluid milk, followed by cheese. Note that Figure 1 has two vertical axes, due to the much higher production volume of fluid milk compared to other dairy products. The right axis corresponds to production volume of fluid milk only, and the left axis corresponds to production volume of the rest of the dairy products shown. The five most prominent states with respect to establishments in the dairy were Wisconsin, California, New York, Pennsylvania and Texas. Wisconsin and California accounted for over a quarter of the total industry establishments.

Typical utility for operations in dairy plants consist of thermal energy, electrical energy, and water. For current heating and cooling systems, thermal energy is supplied mainly in the form of natural gas, which is the dominant source of energy in food processing. The largest share of natural gas consumed by the dairy industry (80%) is used for direct process heating and steam generation via boiler systems. Heating is mainly used for pasteurization, CIP (Cleaning-In-Place) and other heat treatment process. Around 31% of electricity usage is used for process cooling, freezing, and cold storage (Adrian et al, 2011). Jesse and Gould (2005) estimated that both electricity and natural gas represent 40% and 32% of total utility costs, respectively. It was estimated (Sevenster and DeJong, 2008) that the annual carbon dioxide (CO_2) greenhouse gas emissions from dairy processing plants are between 50 and 100g CO_2 per kg milk based up on a study on European Union’s dairy processing. This would translate into total annual CO_2 emissions of tens of millions metric tons associated with energy used in dairy processing plants in the world. Since

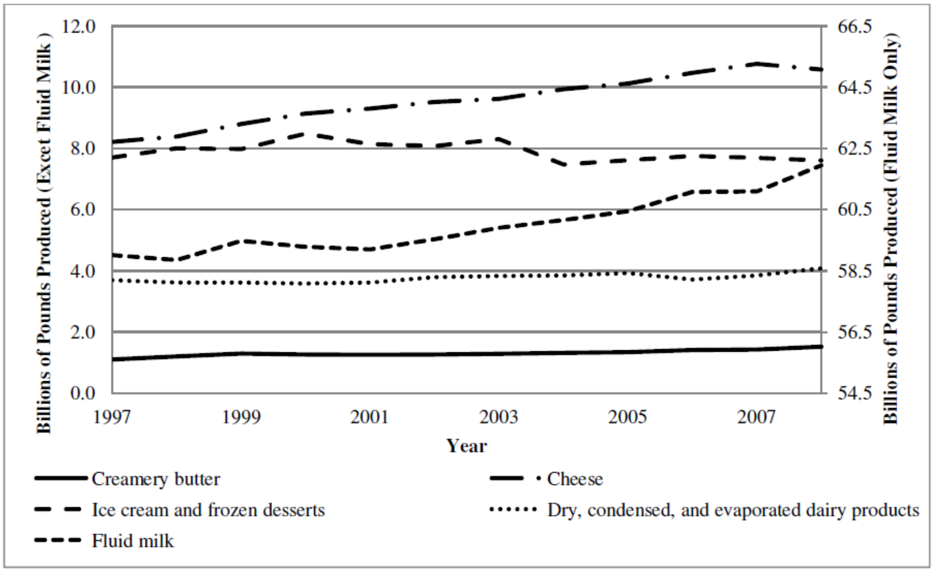


Figure 1: Pounds of dairy produced in the USA during 1997-2008

1998, electricity and natural gas prices have continued to rise dramatically, adding to the economic pressures on the U.S. dairy processing industry. The industry spent nearly $1.5 billion on energy costs in 2008: $726 million for purchased electricity and $731 million for purchased fuels, which consisted primarily of natural gas (Adrian et al, 2011). Given the increases and volatility in industrial natural gas and electricity prices in the United States, the need for improved energy management and energy efficiency in the U.S. dairy processing industry is stronger now than ever.

Currently, information on developing technology to improve the energy efficiency or reduce energy cost for dairy process is limited. Hans et al. (2007) indicated that the use of solar thermal energy in dairy process and other industrial processes was possible. Milk pasteurization with geothermal energy has been reported (John, 1997). In addition, published research on refrigeration or heat pump system to improve the energy efficiency in the dairy processing sector is rather limited. Söylemez (2013) presented a thermo economic optimization simulation for estimating the optimum operating conditions of interconnected heat pump-refrigeration systems that are used in milk pasteurizing applications. There is no CO_2 heat pump application in dairy industry reported.

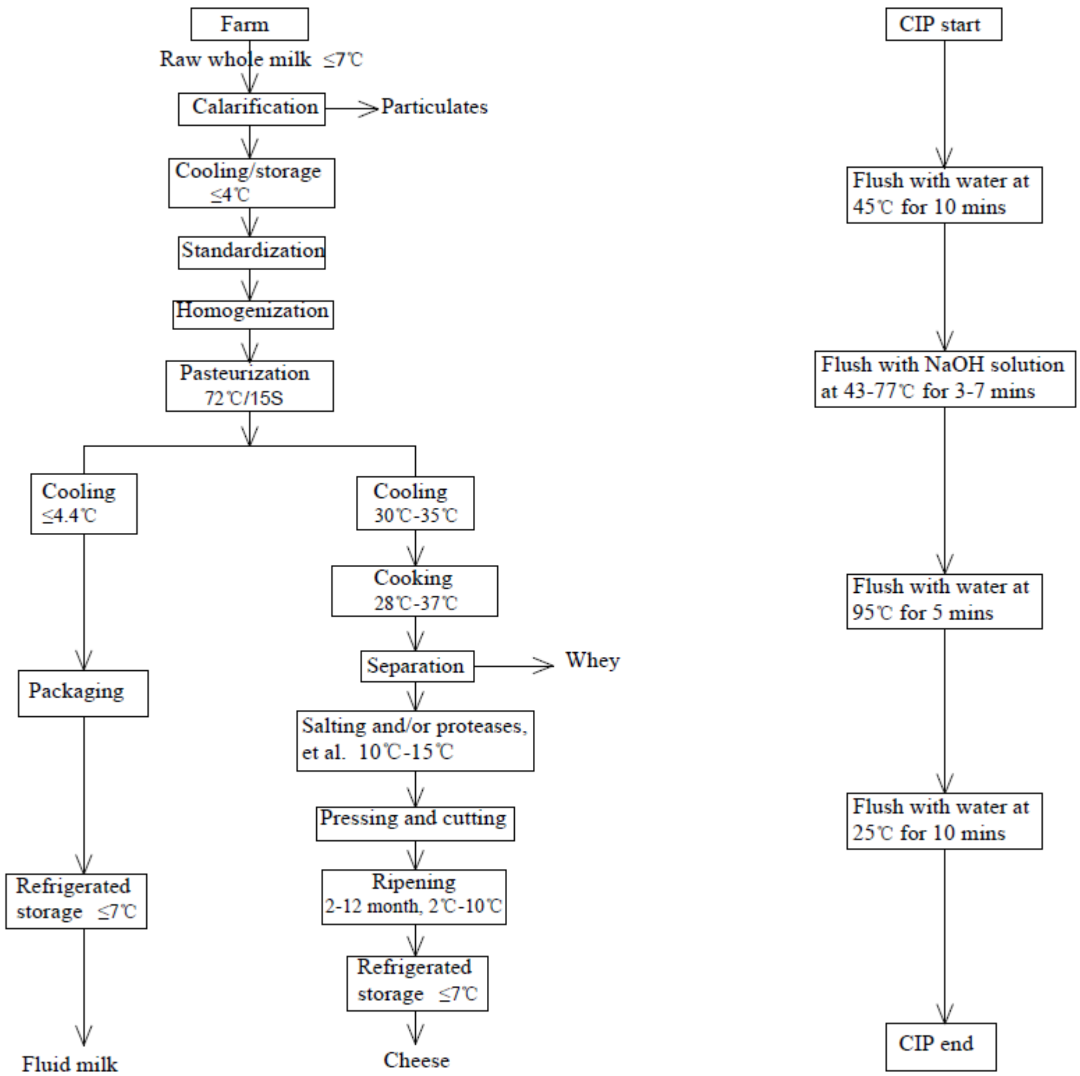
In this paper, a novel CO_2 heat pump system is proposed for dairy processes. It can meet the heating and cooling requirements of dairy manufacturing process simultaneously. The CO_2 heat pump is more efficient and suitable than HFC-based heat pumps to meet the requirement of a heating temperature of up to 95℃. The CO_2 heat pump system characteristics and energy-saving performance are simulated and analyzed. Compared to current heating and cooling system, the CO_2 heat pump can save primary energy of up to 51.5%.

2. METHODOLOGY

2.1 Requirements of heating and cooling during dairy manufacturing process

In dairy plants, the requirements of heating or cooling are associated with processes of pasteurization (e.g., heating), cooling, cooking, storage, biological conversion (e.g., ripening), and cleaning-in-places (CIP), as shown in Figure 2 (Adrian et al, 2011; Ramı´rez, et al., 2006). It depicts a schematic overview of the main processes of fluid milk, cheese and CIP in the dairy plants, where the treatment temperatures and processes are a little different, depending on standards, type of production and individual plants. The requirements of cooling and heating temperatures range from 4℃ to 95℃, respectively.

The United States Public Health Service/Food and Drug Administration (USPHS/FDA) recommended Grade "A" PMO (Grade "A" pasteurized milk ordinance) is the basic standard for dairy process used in the USA.



a) b)

Figure 2: The representative processes for a) fluid milk and cheese production, b) Cleaning-In-Places (**CIP**)

The ordinance regulates the production, transportation, processing, handling, sampling, examination, labeling, and sale of Grade "A" milk and milk products. It requires that all milk produced at a processor and intended for consumption must be pasteurized, which requires that milk must be heated to 72℃ for at least 15 seconds or follow another effective time/temperature combination, and then immediately cooled to 4.4℃ or less to slow spoilage caused by microbial growth in the food. HTST (high-temperature, short-time,) with 72℃ for 15 sec is the most common temperature/time combination used in dairy plants. Pasteurization is the only practical, commercial measure, which if properly applied to all milk, will destroy all milk borne disease organisms. Federal law also requires that dairy and other food processors adhere to certain standards of cleanliness and sanitation for their processing equipment. This is most commonly achieved by a CIP (Cleaning-in-Place) technique. Grade "A" PMO requires that all milk containers, utensils and equipment must be treated with an effective sanitizer before each usage. *The* cleaning process includes several steps, for example, flush with warm water at 45℃ for 10 minutes (Yee, et al., 2013); hot alkaline detergent solution (49℃, 2.66% NaOH for 7 mins or other effective time/temperature combination) is circulated through the equipment to remove milk organics such as carbohydrates, proteins and fats, as well as general soil that was not removed from the initial water rinse, and then drained. It is also used for case washing and general plant cleaning. CIP can account for a significant portion of the energy use in a typical process. For example, Ramı´rez, et al. (2006) estimated that in the Dutch dairy industry, CIP accounts for 9.5% of energy use in fluid milk processing, 26% of energy use in butter processing, and 19% of energy use in cheese production.

2.2 Design of a CO_2 Heat Pump System for Dairy Processes

Figure 3 shows the current heating and cooling systems for dairy processes. Heating is supplied with natural gas or a coal-fired boilers and cooling is supplied with electrically driven HFC refrigeration systems. These systems consume large amounts of natural gas. According to the requirements of simultaneous heating and cooling, a novel transcritical CO_2 heat pump is presented for dairy process applications. The system can meet the heating and cooling requirements at the same time. Figure 4 shows the proposed system schematic of the CO_2 heat pump and Figure 5 shows its state points in a pressure-enthalpy diagram. The novel CO_2 heat pump has the following distinctive features:

(1) Suction temperature is higher than that of current heat pumps.
(2) Two internal heat exchangers are involved in the cycle.
(3) Two gas coolers are involved in the cycle.

In order to produce more and higher temperature hot water, the suction temperature is set to 70℃ which is higher than that of current heat pumps. Two internal heat exchangers are involved in the cycle to improve the $COP_{(heating)}$

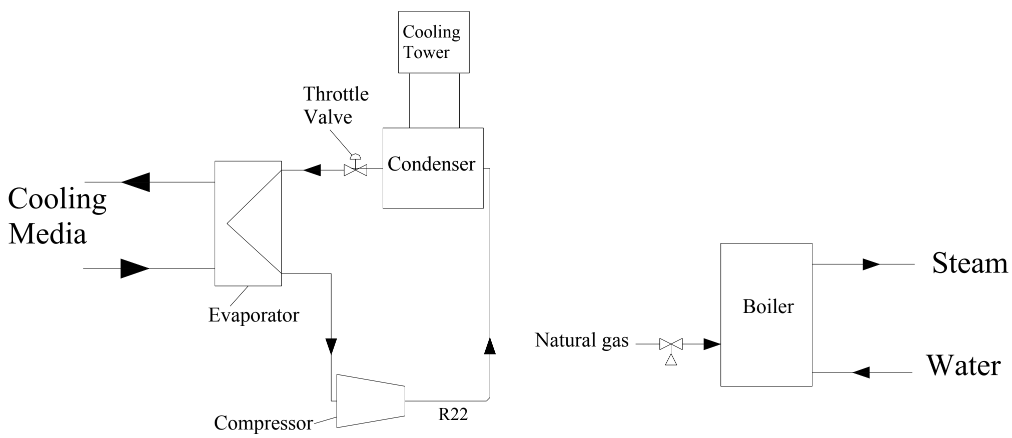


Figure 3: Current heating and cooling system for dairy process

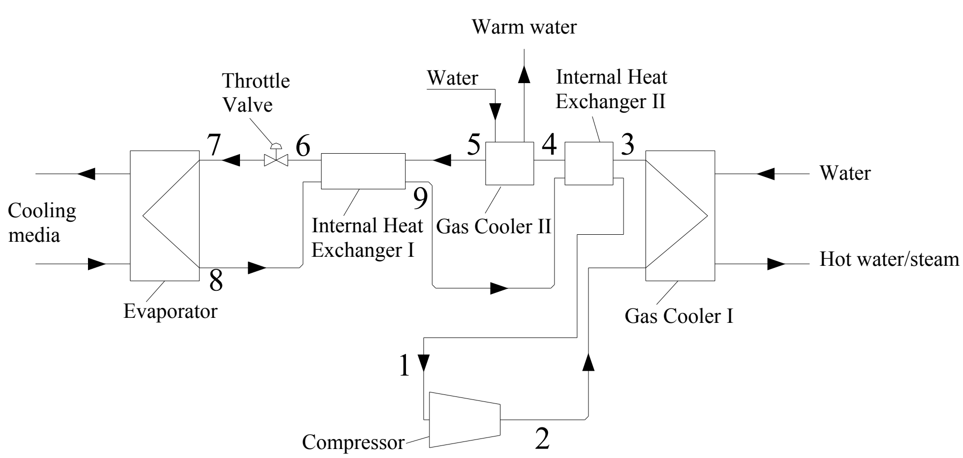


Figure 4: Proposed system schematic of CO_2 heat pump for dairy process

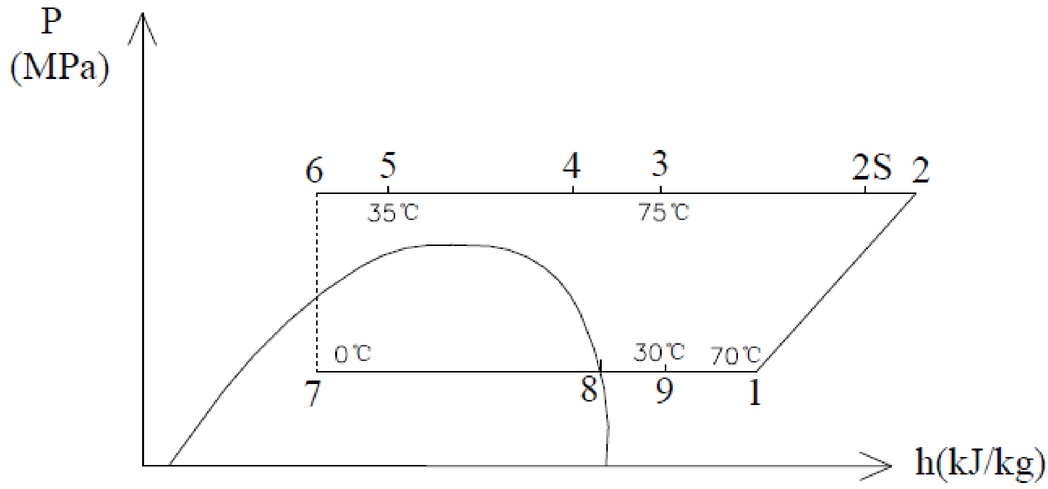


Figure 5: Pressure-enthalpy plots of CO_2 heat pump proposed for dairy process

and $COP_{(cooling)}$.The internal heat exchanger I is used to improve $COP_{(cooling)}$, and the internal heat exchanger II is used to improve $COP_{(heating)}$ and increase the suction temperature. Two gas coolers are involved to produce hot water and warm water, respectively. Hot water is produced by gas cooler I for pasteurization and other heat treatment process with higher temperature requirement (e.g. 72℃-95℃), and warm water is produced by gas cooler II for cooking process and other heat treatment process with lower temperature requirement (e.g. 25℃-50℃). Gas cooler II can also be used as a pre-heater in certain situations.

3. SIMULATION RESULTS OF PRIMARY ENERGY-SAVING

3.1 Analysis of the CO_2 Heat Pump Technical Characteristics

Table 1 lists the parameters that are used to analyze the technical characteristics of the CO_2 heat pump. The COP is defined by the following equations:

$$COP_{(cooling)}=(h_8-h_7)/(h_2-h_1) \tag{1}$$

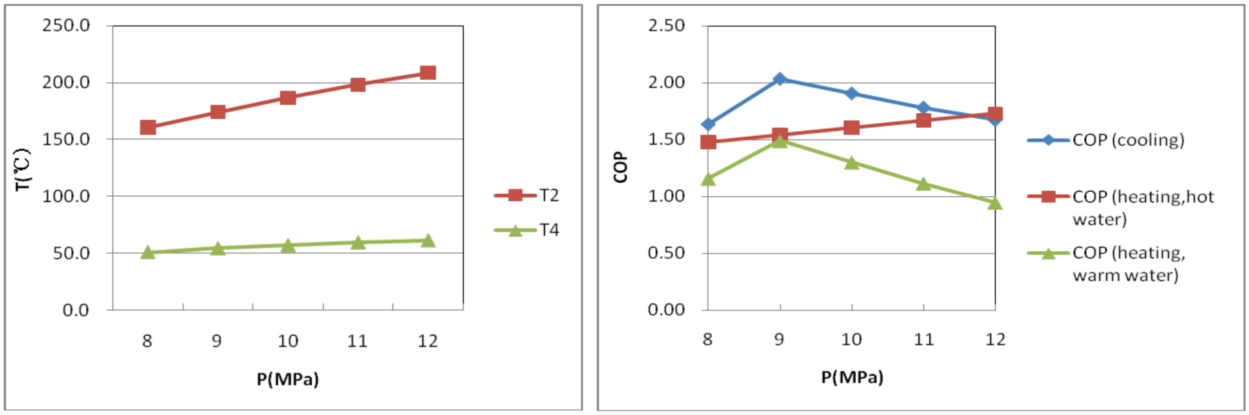
$$COP_{(heating,\ hot\ water)}= (h_2-h_3)/(h_2-h_1) \tag{2}$$

$$COP_{(heating,\ warm\ water)}=(h_4-h_5)/(h_2-h_1) \tag{3}$$

Figure 6 shows the simulation results of the CO_2 heat pump system. It is found that with the increase of discharge pressure P, the discharge temperature T_2 and T_4 (CO_2 inlet temperature of gas cooler II) both increase. At the same time, the $COP_{(cooling)}$ and $COP_{(heating,\ warm\ water)}$ increase and then decrease, but the $COP_{(heating,\ hot\ water)}$ consistently increases. When the discharge pressure is 9 MPa, the $COP_{(cooling)}$ has the highest value. Therefore, the following analysis is based on this operating condition. It is important to note that the discharge temperature is higher than that of current heat pumps. Therefore, a new kind of lubricating oil is needed to make the CO_2 compressor work normally under high discharge temperature conditions.

Table 1: Baseline parameters of the CO_2 heat pump system

NO.	State point	Temperature (℃)	Pressure (MPa)	Remark
1	1	70	3.485	Superheat degree is 70℃
2	3	75	8-12	
3	5	35	8-12	P5=P3
4	8	0	3.485	Saturate gas point
5	9	30	3.485	



a) Discharge temperature T_2 and T_4 b) COP

Figure 6: Simulation results and COP of the CO_2 heat pump

3.2 Primary Energy-Savings Potential Analysis of the CO_2 Heat Pump

The following assumptions are made to simulate the performance of primary energy-savings and the operating cost:
(1) The fuel-to-steam efficiency of the natural gas boiler is 0.7 (range: 0.60-0.85).
(2) The heating value of natural gas from combustion is 35335 kJ/m^3.
(3) Natural gas power generation efficiency is 0.32.
(4) Current system means that the heating is supplied with a natural gas boiler, and the cooling is supplied with an R22 refrigeration system with $COP_{(cooling)}$ equal to 3.0.

Table 2: The highest primary energy-saving rate of the CO_2 heat pump

NO.				1	2
System Type				Traditional System	CO_2 Heat Pump
Cooling		Cooling Capacity	kJ/kg	100	
		System		Refrigeration (R22)	CO_2 Heat Pump
		$COP_{(cooling)}$		3.0	2.03
		Electricity Consumption	kJ/kg	33.33	49.26
			kWh/kg	0.0093	0.0137
		Source of Power Generation		Nature Gas	
		Efficiency of Power Generation		0.32	
		Natural Gas Consumption	m^3/kg	0.00283	0.00425
Heating	Hot Water	Source		Natural Gas	CO_2 Heat Pump (Rejected Heat from Gas Cooler I)
		Efficiency/ $COP_{(heating, hot water)}$		0.70	1.54
		Heating Capacity	kJ/kg	75.86	
		Natural Gas Consumption	m^3/kg	0.00311	0
	Warm Water	Source	kJ/kg	Natural Gas	CO_2 Heat Pump (Rejected Heat from Gas Cooler II)
		Efficiency/ $COP_{(heating, warm water)}$		0.70	1.49
		Heating Capacity	kJ/kg	73.40	
		Natural Gas Consumption	m^3/kg	0.00283	0
Comparison on Primary Energy		Total Natural Gas Consumption	m^3/kg	0.00877	0.00425
		Primary Energy-saving	m^3/kg	—	0.00452
			%	—	51.5

Based on the assumption that all cooling water, hot water/steam and warm water heated by the CO_2 heat pump are fully utilized, the simulated results are showed in Table 2.

The required cooling capacity is supposed to be 100 kJ/kg, which does not affect the value of the primary energy-savings rate. It can be found that the highest primary energy-savings rate of the CO_2 heat pump is as high as 51.5%. It is due to the fact that all of hot water and warm water produced by CO_2 heat pump is free, but for current system, there is a need of vast natural gas to heat water, even though the COP of the CO_2 heat pump is lower than that of the R22 refrigeration system. In other words, the primary energy-savings rate of 51.5% is the highest possible potential under this operating condition. For different dairy products, the requirements of heating capacity and cooling capacity are vary due to different manufacturing process, so the primary energy-saving rate will also vary and is not higher than 51.5%. The fluid milk and cheese are main dairy products, so the following simulation of primary energy-saving and operating cost are analyzed for the two kind of dairy products.

3.3 Primary Energy-Savings Analysis of the CO_2 Heat Pump for Fluid Milk and Cheese Manufacturing Processes

For fluid milk manufacturing processes, the generated heat is used in processes such as pasteurization, deodorization and CIP, while the cooling demand is used in cooling, final storage, pre-packaging storage, receiving and storage processes. In typical U.S. dairy processing facilities, the required cooling intensity, heating intensity with hot water and warm water are 358.0 kJ/kg milk, 271.0 kJ/kg milk and 72.0 kJ/kg milk, respectively (Adrian et al, 2011). The energy-savings performance of the CO_2 heat pump for fluid milk processes is showed in Table 3. I It can be seen that the primary energy-savings rate is 36.0% which is lower than the highest possible value of 51.5%. This is because the required heating intensity is lower than the one that the CO_2 heat pump can supply.

Table 3: Energy-savings performance of CO_2 heat pump application in fluid milk processes

NO.				1	2
System Type				Current System	CO_2 Heat Pump
Cooling		Required Cooling Intensity	kJ/kg	358.0	
		System		Refrigeration(R22)	CO_2 Heat Pump
		$COP_{(cooling)}$		3	2.03
		Electricity Consumption	kJ/kg	119.33	176.35
			kWh/kg	0.0331	0.0490
		Source		Nature Gas	
		Efficiency of Power Generation		0.32	
		Natural Gas Consumption	m^3/kg	0.01047	0.01556
Heating	Hot Water	Required Heating Intensity	kJ/kg	271.0	
		Source		Nature Gas	CO_2 Heat Pump (Rejected Heat from Gas Cooler I)
		Efficiency/ $COP_{(heating, hot water)}$		0.7	1.54
		Natural Gas Consumption	m^3/kg	0.01104	0
	Warm Water	Required Heating Intensity	kJ/kg	72.00	
		Source		Nature Gas	CO_2 Heat Pump (Rejected Heat from Gas Cooler II)
		Efficiency/ $COP_{(heating, warm water)}$		0.7	1.49
		Natural Gas Consumption	m^3/kg	0.00283	0
Comparison on Primary Energy		Total Natural Gas Consumption	m^3/kg	0.02434	0.01557
		Primary Energy-saving	m^3/kg	—	0.00878
			%	—	36.0

Table 4: Energy-savings analysis of CO_2 heat pump application in cheese manufacturing processes

NO.				1	2
System Type				Current system	CO_2 heat pump
Cooling		Required Cooling Intensity	kJ/kg	1088.70	
		System		Refrigeration (R22)	CO_2 Heat Pump
		$COP_{(cooling)}$		3	2.03
		Electricity Consumption	kJ/kg	362.90	536.31
			kWh/kg	0.1008	0.1490
		Source		Nature Gas	
		Efficiency of Power Generation		0.32	
		Natural Gas Consumption	m^3/kg	0.03198	0.04754
Heating	Hot Water	Required Heating Intensity	kJ/kg	825.92	
		Source		Nature Gas	CO_2 Heat Pump (Rejected Heat from Gas Cooler I)
		Efficiency/ $COP_{(heating,\ hot\ water)}$		0.7	1.54
		Natural Gas Consumption	m^3/kg	0.03339	0
	Warm Water	Required Heating Intensity	kJ/kg	527.64	
		Source		Nature Gas	CO_2 Heat Pump (Rejected Heat from Gas Cooler II)
		Efficiency/ $COP_{(heating,\ warm\ water)}$		0.7	1.49
		Natural Gas Consumption	m^3/kg	0.02123	0
Comparison on Primary Energy		Total Natural Gas Consumption	m^3/kg	0.08660	0.04754
		Primary Energy-saving	m^3/kg	—	0.03906
			%	—	45.1

For cheese manufacturing processes, the heat energy is mainly used in processes such as pasteurization, cooking, finishing vat, make vat and CIP. The cooling energy is mainly used in cooling and storage/aging. In typical U.S. dairy processing facilities, the required cooling intensity, heating intensity with hot water and warm water are 1343.28 kJ/(kg cheese), 825.92 kJ/(kg cheese) and 527.64 kJ/(kg cheese) respectively. (Adrian et al, 2011). Due to the fact that $COP_{(cooling)}$ of CO_2 heat pump is lower than that of the R22 refrigeration system, the cooling intensity and the heating intensity should be considered together in order to get the highest primary energy-saving rate during the schematic design phase. In this case, the CO_2 heat pump supplies 1088.70 kJ/kg of the cooling intensity required. At the same time, the required heating intensity of hot water and warm water can also be supplied by the CO_2 heat pump. The rest of cooling intensity 254.58kJ/kg is supplied with R22 refrigeration system. The energy-savings performance of the CO_2 Heat Pump is shown in Table 4. It can be seen that the primary energy-savings rate is 45.1%, which is close to the highest value of 51.5%.

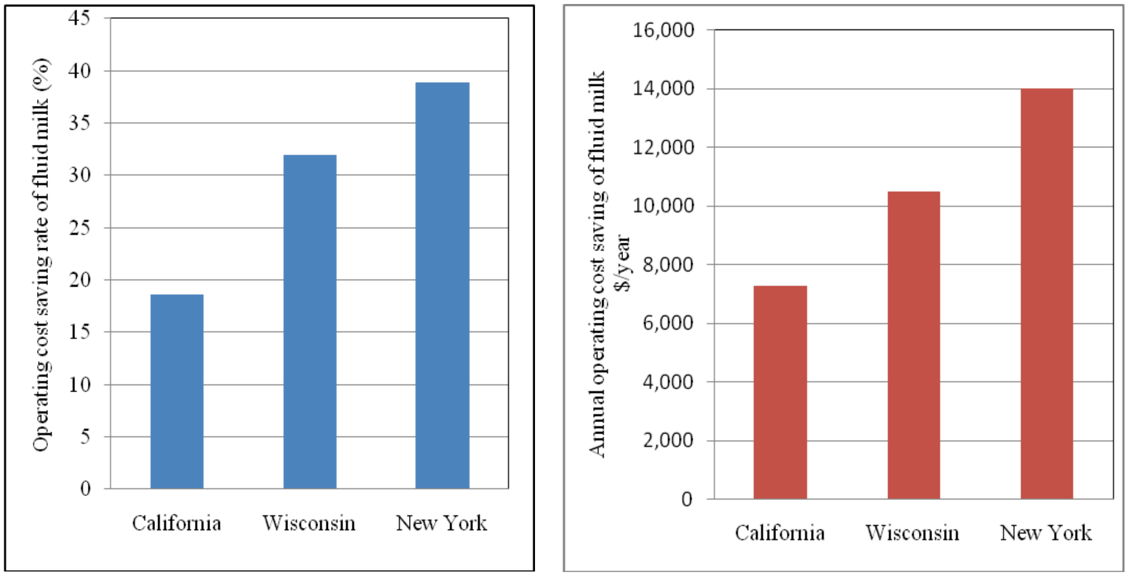
4. OPREATING COST ANALYSIS

The prices of natural gas and electricity will vary as a function of time and state in the USA. Based on the annual average industrial prices in 2012 (DOE, 2014) for states shown in Table 5, the operating cost of fluid milk and cheese production processes are calculated, and the results are showed in Figure 7 and Figure 8, respectively. The analysis of the annual operating cost is based on the following assumptions:

(1) For fluid milk factory, there are 500 cows to provide milk, and one cow can provide 75 pounds milk every day. So, the annual output of fluid milk is 6,208,650 kg/year.
(2) For cheese plants, the annual output of cheese is the same as that of the fluid milk factory for comparison's sake.

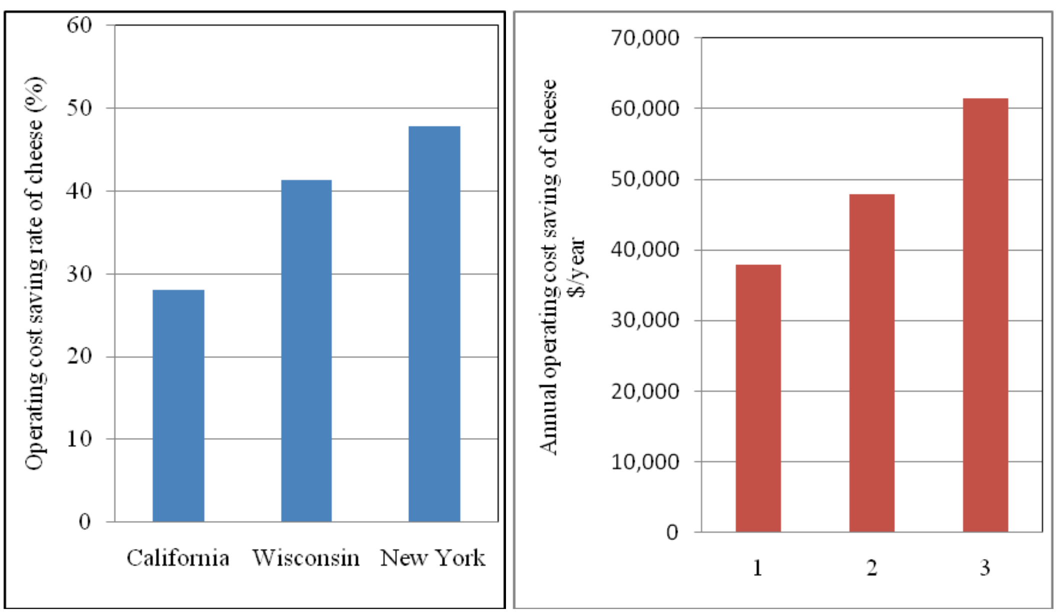
Table 5: Annual average energy prices of three main dairy producing states in 2012

Region		California	Wisconsin	New York
Price of Natural Gas	$/m^3$	0.2039	0.2053	0.2445
Price of Electricity	$/kWh	0.1049	0.0734	0.0723



a) Operating cost saving rate   b) Annual operating cost saving

Figure 7: Operating cost saving of CO_2 heat pump application in fluid milk process



a) Operating cost saving rate   b) Annual operating cost saving

Figure 8: Operating cost saving of CO_2 heat pump application in cheese process

From Figure 7 and Figure 8, it can be seen that the operating cost increases as the price of natural gas and electricity increase. For fluid milk processes, the range of operating cost saving rate is from 18.6% to 38.9% in Wisconsin, California and New York State. For cheese processes, the range of operating cost saving rate is from 28.1% to 47.9% in the three States. Comparing Figure 8 with Figure 7 indicates that the operating cost saving rate of cheese is higher than that of fluid milk in the same state. This is because the required heating and cooling intensity of cheese is much higher than that of fluid milk, which is also shown by the fact that the annual operating cost saving of cheese is much higher than that of fluid milk.

5. CONCLUSIONS

In order to reduce the energy consumption and greenhouse gas emissions in dairy processes, a novel tanscritical CO_2 cycle heat pump is proposed and analyzed. The characteristics of the CO_2 heat pump are determined. Compared to the current heating and cooling systems, the primary energy-savings and operation cost saving are predicted.

The highest primary energy-saving rate of the CO_2 heat pump is 51.5%. For fluid milk processes and cheese processes, the CO_2 heat pump can save primary energy of 36.0% and 45.1%, respectively. The operating cost saving rate range is 18.6%-38.9% and 28.1%-47.9% for fluid milk and cheese processes, respectively, which will vary with the prices of natural gas and electricity. In order to get the highest primary energy-saving rate, the cooling capacity and heating capacity supplied by the CO_2 heat pump should be considered simultaneously during the schematic design phase. Based on the requirements of the dairy manufacturing processes, the CO_2 heat pump parameters such as discharge pressure, suction temperature, outlet temperature of two gas coolers, etc., can be optimized for different kinds of dairy manufacturing processes. This type of CO_2 heat pump can also be used in other industrial process.

Future research needs to focus on solving the problem that the compressor can work reliably under high discharge temperature condition using suitable lubricating oils.

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