ID 2674

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

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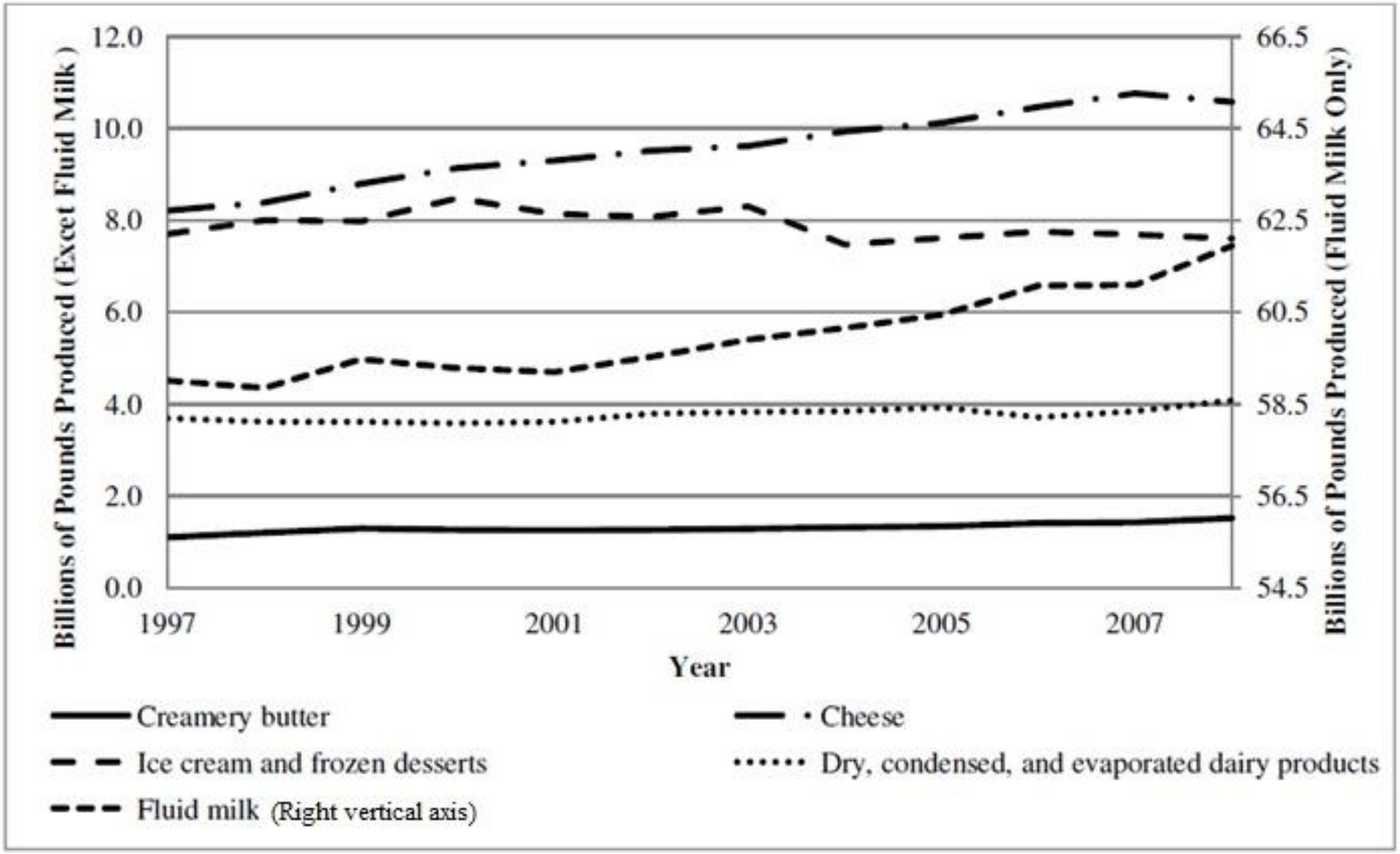
1. INTRODUCTION

Pounds of dairy produced in the USA during 1997-2008



Note:1lb=0.4536kg

Result: The highest production is fluid milk, followed by cheese in USA.

Energy Intensities of Fluid Milk Process

Fluid Milk

Process	Energy Intensity (BTU/lb)				
	Steam	Direct Fuel	Electricity for Refrigeration	Other Electricity	
Final Storage			18		18
Packaging		15			15
Pre-Packaging Storage			9		9
Deoderization	25				25
Cooling			85		85
Homogenization				10	10
Pasteurization	92				92
Separation				18	18
Clarification/Standardization				9	9
Receiving and Storage		13	18		30

Note: 1BTU/lb=2.326 kJ/kg

For fluid milk: fuel for heating — 343 kJ/kg
electricity for refrigeration — 0.084 kWh/kg

Energy Intensities of Cheese Process

Cheese

Process	Energy Intensity (BTU/lb)				
	Steam	Direct Fuel	Electricity for Refrigeration	Other Electricity	Total
Cooking, Pasteurization	92				92
Finishing Vat	8				8
Make Vat	178				178
Starter Media	6				6
Pasteurization	72				72
Motors, Pumps			193	648	841

Note: 1BTU/lb=2.326 kJ/kg

For cheese: fuel for heating — 1481 kJ/kg

electricity for refrigeration — 0.124 kWh/kg

In total: Fuels and electricity: $1.5 billion/year in USA

Greenhouse gas emissions: 50 – 100 g CO_2/kg

Fluid milk and cheese processes with heating and cooling requirements

a) fluid milk and cheese b) Cleaning-In-Places

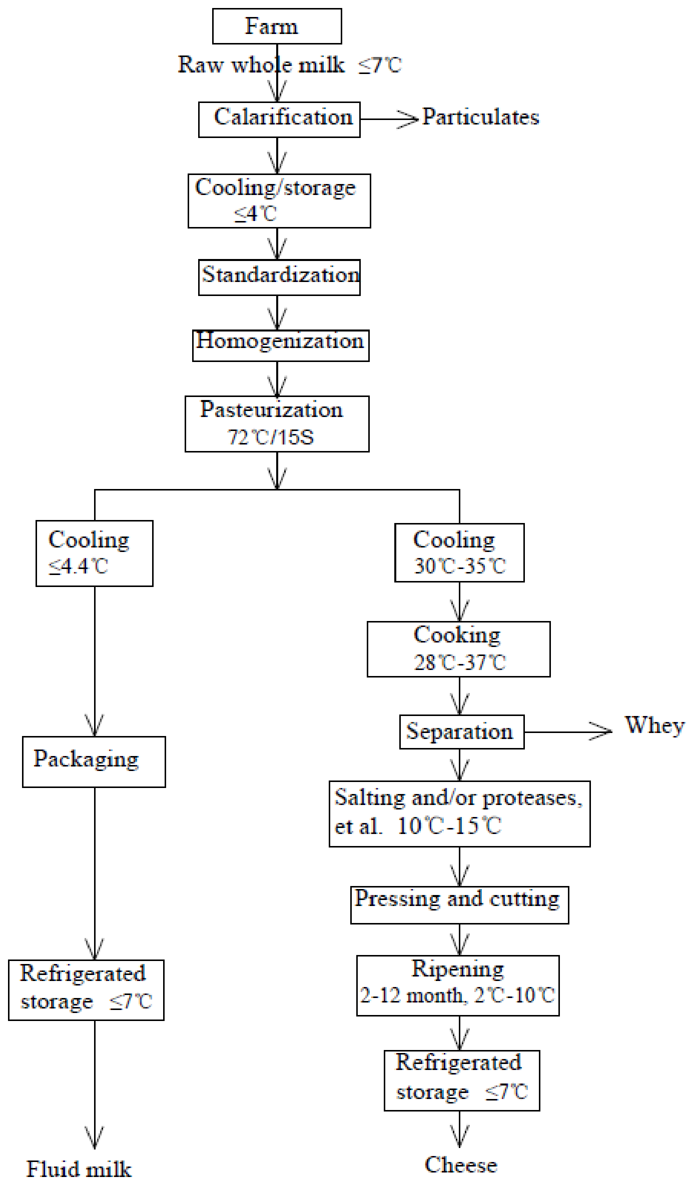
Requirements:

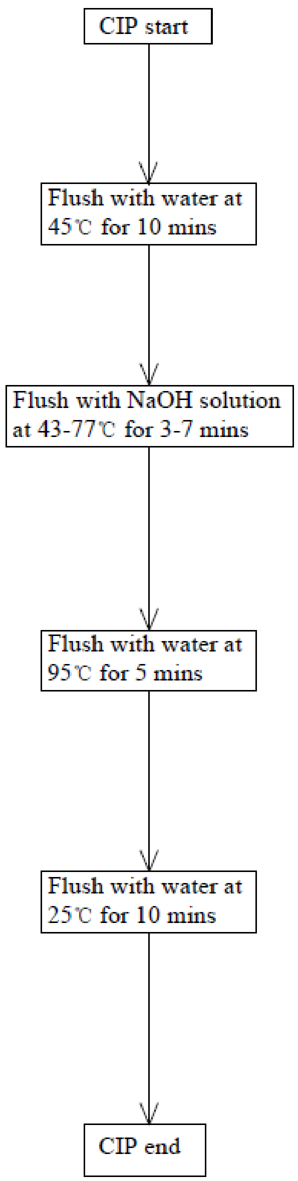
Heating water:

25℃ - 95℃

Cooling water:

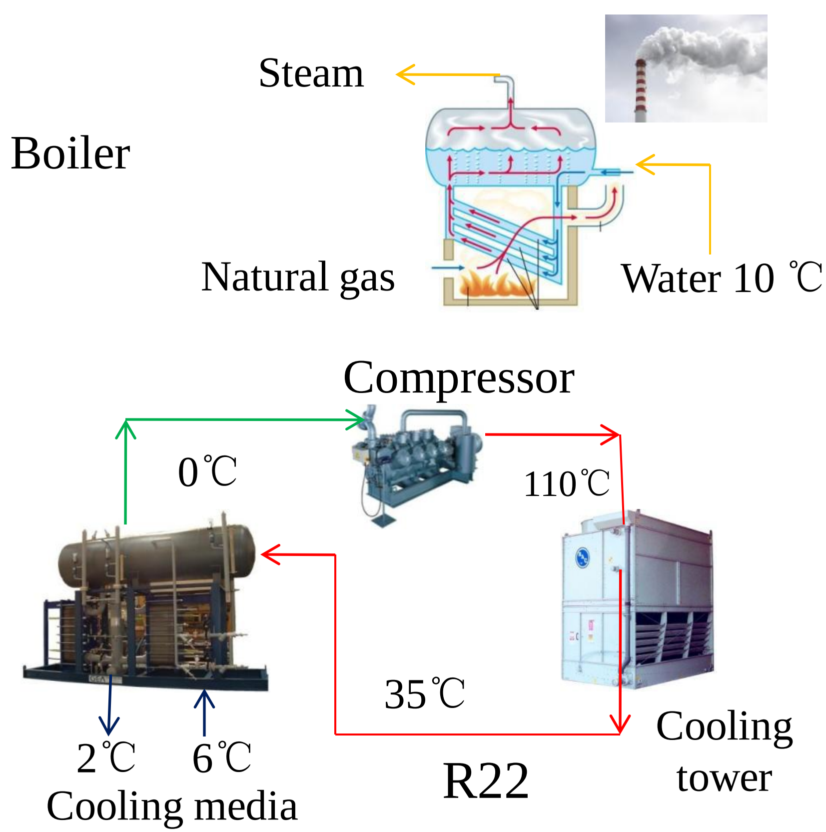
4℃ - 15℃



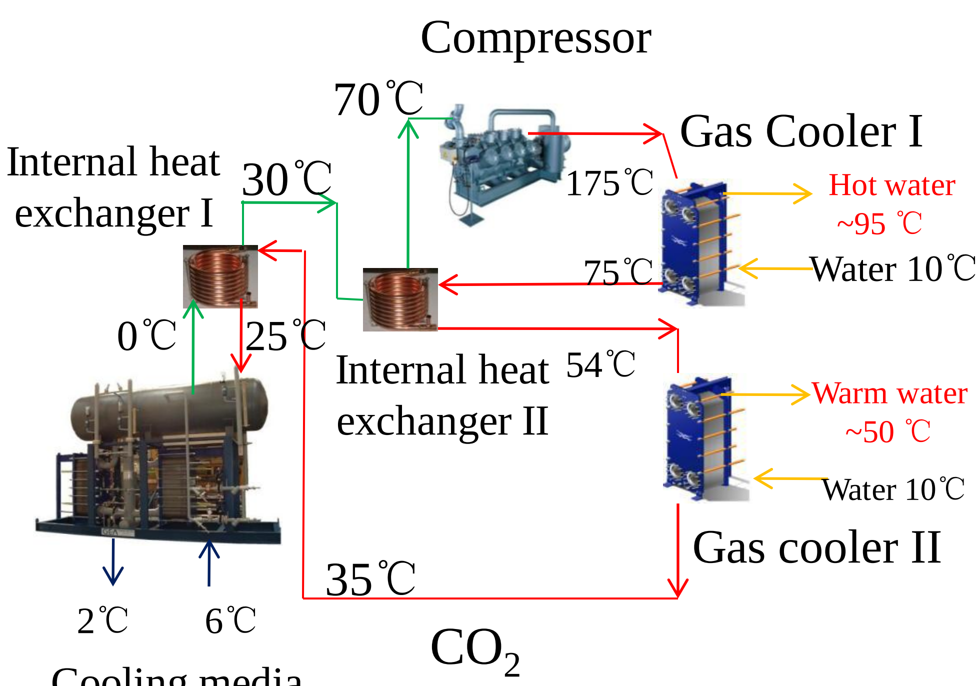


2. METHODOLOGY

Current heating and cooling system



Proposed novel CO_2 heat pump



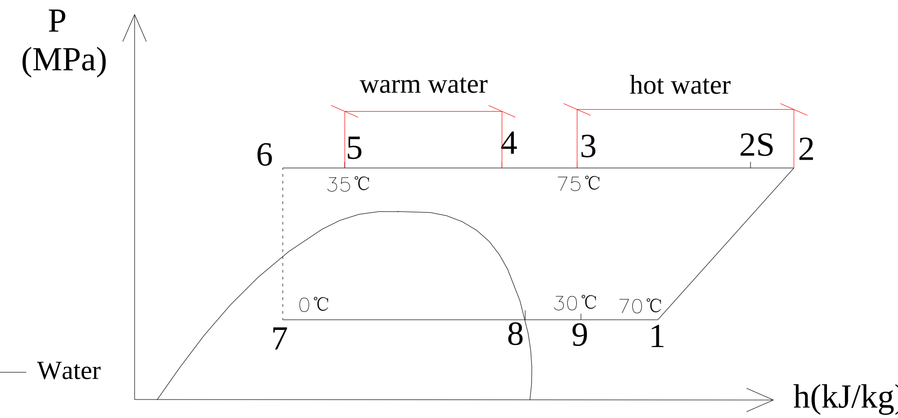
Novel CO_2 heat pump system and P-h diagram

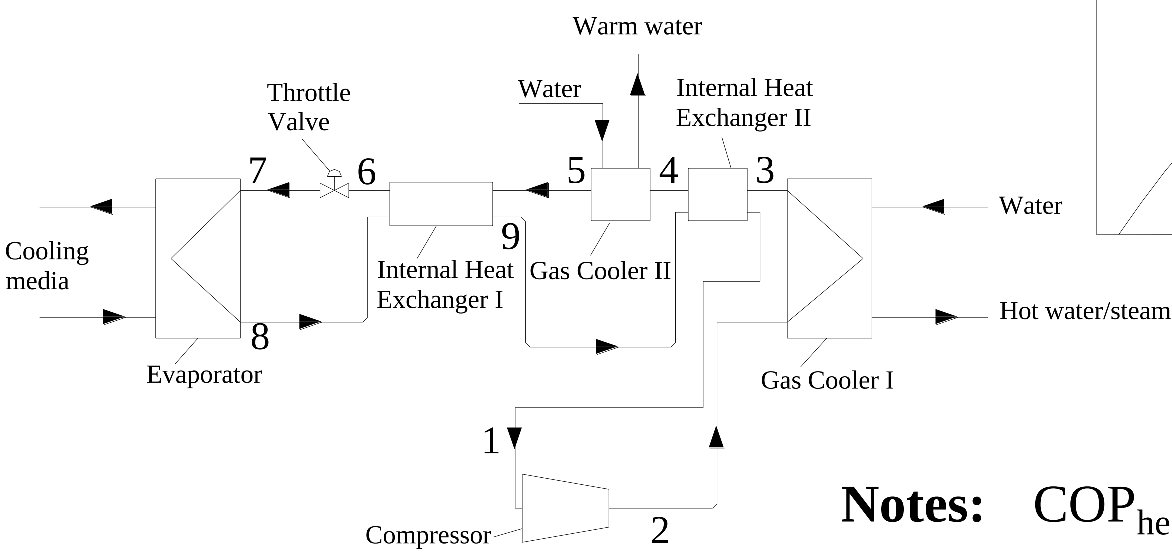
Novel CO_2 heat pump features:

(1) Higher suction and discharge temperatures than current heat pumps

(2) Two internal heat exchangers

(3) Two gas coolers





Notes:

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

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

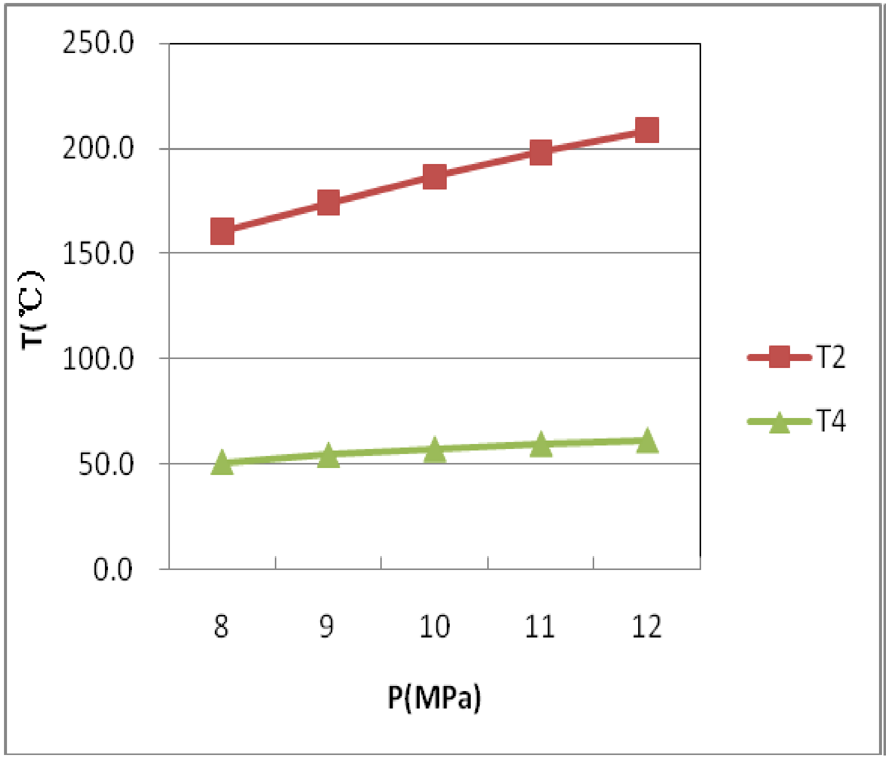
$$COP_{cooling} = (h_8-h_7)/(h_2-h_1)$$

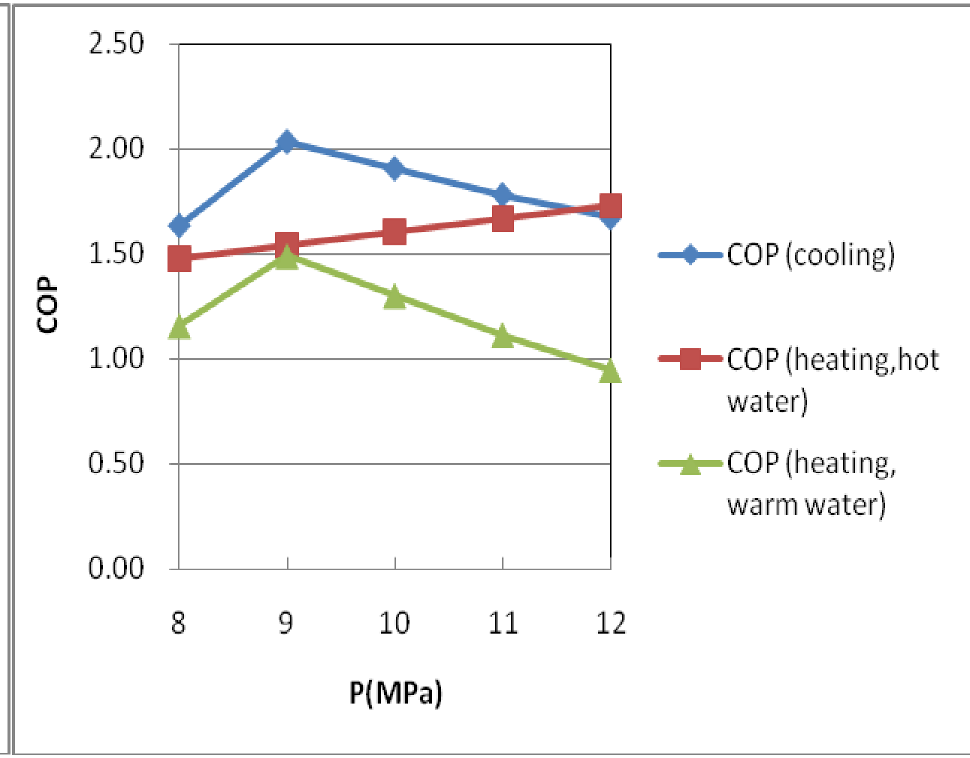
3. SIMULATION OF CO_2 HEAT PUMP

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 K
2	3	75	8-12	
3	5	35	8-12	$P_5=P_3$
4	8	0	3.485	Saturated vapor point
5	9	30	3.485	

Simulation Results of CO_2 Heat Pump





T_2: heating temperature of hot water (discharge temperature)
T_4: heating temperature of warm water

Result at P = 9 MPa: $COP_{cooling} = 2.03$

$COP_{heating,warm\ water} = 1.49$. optimal values.

Primary Energy-Savings of the CO_2 Heat Pump

Assumptions:

(1) Current system:

heating — natural gas boiler, efficiency: $\eta = 0.7$
cooling — R22, $COP_{cooling} = 3.0$

(2) Proposed CO_2 heat pump:

heating — gas coolers $COP_{heating,hot\ water} = 1.54$
$COP_{heating,warm\ water} = 1.49$

cooling — $COP_{cooling} = 2.03$

(3) Natural gas power generation efficiency: 0.32

Highest primary energy-saving rate of the CO_2 heat pump (51.5%)

NO.				1	2
System Type				Current System	CO_2 Heat Pump
Cooling		Cooling Capacity	kJ/kg	100	
		Natural Gas Consumption	m^3/kg	0.00283	0.00425
Heating	Hot Water	Heating Capacity	kJ/kg	75.86	
		Natural Gas Consumption	m^3/kg	0.00311	**0**
	Warm Water	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**

Primary energy-saving of CO_2 heat pump in fluid milk process (36.0%)

NO.				1	2
System Type				Current System	CO_2 Heat Pump
Cooling		Cooling Capacity	kJ/kg	358	
		Natural Gas Consumption	m^3/kg	0.01047	0.01556
Heating	Hot Water	Heating Capacity	kJ/kg	271.0	
		Natural Gas Consumption	m3/kg	0.01104	0
	Warm Water	Heating Capacity	kJ/kg	72.0	
		Natural Gas Consumption	m3/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**

Primary energy-saving of CO_2 heat pump in cheese process (45.1%)

NO.				1	2
System Type				Current System	CO_2 Heat Pump
Cooling		Cooling Capacity	kJ/kg	1088.70	
		Natural Gas Consumption	m^3/kg	0.03198	0.04754
Heating	Hot Water	Heating Capacity	kJ/kg	825.92	
		Natural Gas Consumption	m^3/kg	0.03339	0
	Warm Water	Heating Capacity	kJ/kg	527.64	
		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**

4. OPREATING COST ANALYSIS

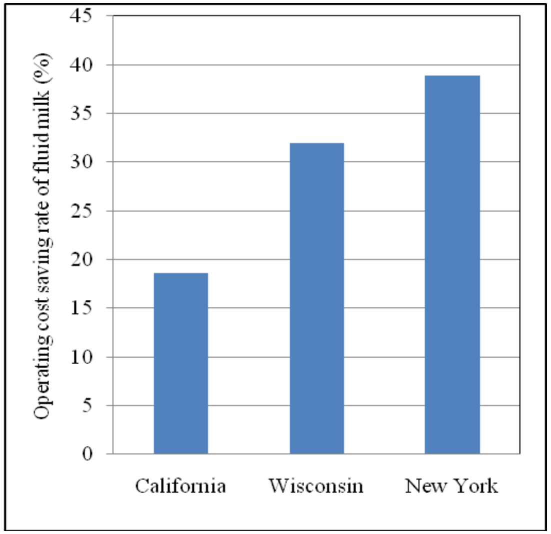
Wisconsin, California and New York are the most prominent production states for the dairy.

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

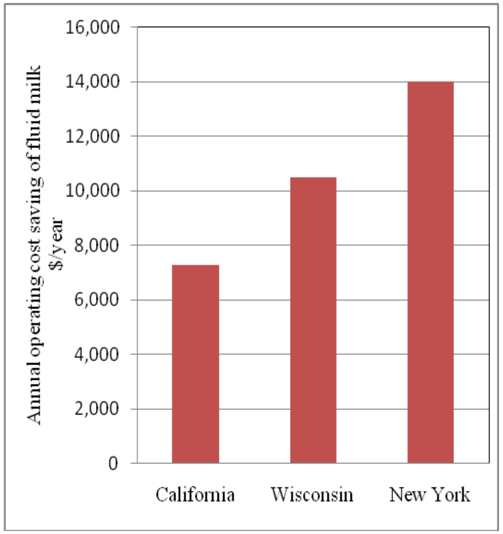
Region		California	Wisconsin	New York
Price of Natural Gas	$/m^3$	0.2039	0.2053	0.2445
Price of Electricity	$/kWh	0.1049	0.0734	0.0723

Operating cost saving of CO_2 heat pump in fluid milk process

a) Operating cost saving rate (18.6%-38.9%)

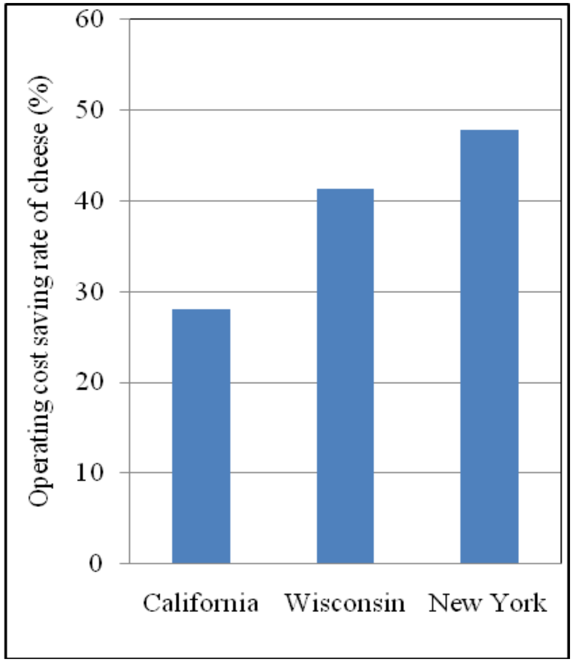


b) Annual operating cost saving with 6,208,650kg/year

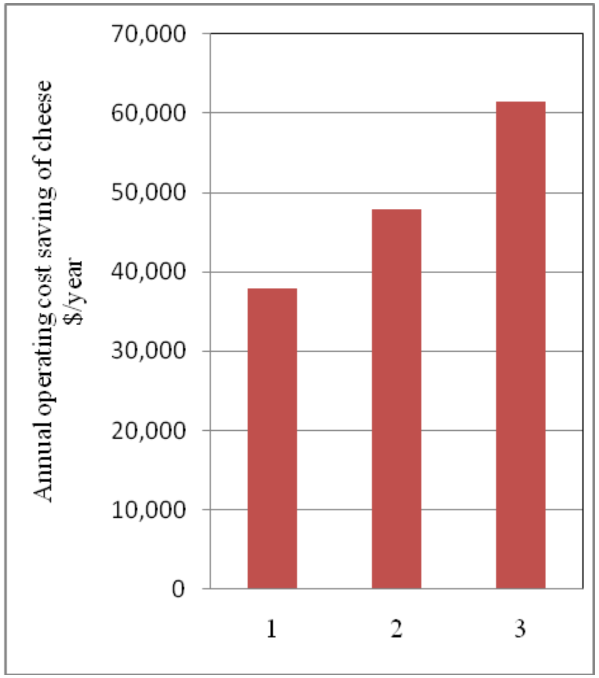


Operating cost saving of CO_2 heat pump in cheese process

a) Operating cost saving rate (28.1%-47.9%)



b) Annual operating cost saving with 6,208,650 kg/year



Results:

(1) For fluid milk, operating cost saving rate: 18.6% - 38.9%.

(2) For cheese, operating cost saving rate: 28.1% - 47.9%.

(3) The operating cost saving increases as the price of natural gas increases.

5. CONCLUSIONS

(1) A novel transcritical CO_2 cycle heat pump is proposed for dairy processes.

(2) The highest primary energy-saving rate of the CO_2 heat pump is 51.5%.

(3) For fluid milk processes and cheese processes, the CO_2 heat pump can save primary energy of 36.0% and 45.1%, respectively.

(4) The operating cost saving rate range is 18.6%-38.9% and 28.1%-47.9% for fluid milk and cheese processes, respectively.

(5) 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 processes.

(6) This type of CO_2 heat pump can also be used in other industrial process.

(7) Next work is to solve the problem that CO_2 compressor can work under high discharge temperature.

Thank you!

Any questions?