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A Trans-critical CO2 Heat Pump System for Waste Heat Utilization in Warm Weather Condition Applied to a Milk Refrigeration Plant

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ABSTRACT

Based on field data from a medium scale ammonia based milk refrigeration plant located in northern part of India, a trans-critical CO_2 based heat pump system is conceptualized to utilize the waste heat from the plant to improve overall coefficient of performance. Year round plant operating data is collected. The plant handles in the range of 0.1 to 0.15 million liters of milk and milk products daily. It maintains two cooling chambers, one at 4°C and the other at -10°C. Every seven days it is required to replenish a 5000 liter tank with ground water for evaporative cooling of the system. Up-stream and down-stream processes in the milk processing plant utilizes a coal fired boiler system which also uses ground water.

In this study, the condenser of the ammonia based refrigeration system is coupled with the evaporator of the proposed CO_2 trans-critical heat pump system which is maintained at 20°C round the year. The heat pump delivers heat at about 70°C to pre heat the boiler feed water available in temperature range 25° to 29°C round the year. Augmentation of the proposed CO_2 system is able to reduce coal consumption by utilizing the waste heat from the ammonia system at the same time reduce ground water utilization by eliminating evaporative cooling. The proposed heat pump system has encouraging COP and is designed to be largely independent of variation in ambient temperature. Based on field data, a comparative study is carried out using thermodynamic & thermo-economic analysis for a duration of one year to establish feasibility of the proposed system.

1. INTRODUCTION

Indian dairy industry offers tremendous opportunity for entrepreneurs, being one of the world's largest and fastest growing markets for milk and milk products. Domestic dairy production is expected to rapidly expand in terms of variety and volume (Anstett, 2006). India is the second largest milk producer in the world producing estimated 137.7 MT of milk at present. By 2021 Indian's milk production is projected to equal that of the whole European Union (FAO, 2015). Also, India is the second largest country in milk consumption, estimated 129.2 MT per year.

Current requirement is research focused on energy saving, environment protection & waste reduction in milk production and handling. Operations in dairy plants demand thermal energy, electrical energy and copious amounts of water. Typically, in India, low grade coal (~3500 calorific value) is used to run the boilers to fulfill the heating demand. These boilers have historically proven to be effective sources of energy in dairy industries. Significant proportion of thermal energy demand (about 75%) for heating and steam generation purpose in dairy plants are met by the coal fired boilers. The rest (about 25%) is met through thermopacks using HSD and heaters using electricity. Electricity is also used for running the refrigeration plant, for lighting and automation. Ammonia based vapor compression refrigeration systems are by far the most preferred mode for cooling in milk processing plants. A variety of products are handled by these plants like butter, ice cream, curd, condensed milk, butter milk, flavored milk, cheese, etc. There is also a large seasonal variation in milk supply quantity as well as its demand.

Brush *et al.* (2011) explored, impact of processes carried out in dairy industry and opportunities of waste recovery from the effluent streams. In a recent study, Yefeng *et al.* (2014) employed CO_2 heat pump system in dairy industry to partially meet the heating demand and study the overall energy saving and its impact on the operating cost.

We propose to incorporate a CO_2 trans-critical heat pump system to utilize the rejected heat from the ammonia based refrigeration plant in order to preheat boiler feed water and thereby reduce coal consumption. The boiler feed water is ground water that is available round the year at more or less constant temperature. The condenser of ammonia based refrigeration system is coupled with evaporator of the heat pump system such that the evaporative cooling system is eliminated resulting in saving of some ground water. The CO_2 system COP is now coupled to ground water that is available at around 27°C. The objective of this study is to evaluate the feasibility of such a plant for a milk refrigeration unit using the actual heating & cooling demand data from plant and its seamless utilization with on-site installations. The resulting change in primary operating cost and energy saving thereof are also computed.

2. PLANT DESCRIPTION

Towards fulfillment of the national objective of making India sufficient in milk production, milk plant Verka was established in 1963 and located at Amritsar in Punjab. The currently operating boiler unit here was established in 2008 and the ammonia based refrigeration system in 2011.

To handle required cooling demand for post processing storage of milk & milk products, an ammonia based refrigeration plant of 140 TR capacity is employed. It maintains two chambers at 4ºC and -10ºC respectively. Due to supply as well as demand fluctuation, the milk handling load varies, from 1,50,000 liters/day in winter to about 70,000 liters/day during summer. To cater to this load variation, the plant is operated either in two shifts or three shifts. Heat from the ammonia based refrigeration system is rejected using evaporative cooling arrangement as shown in Figure 1. Forced air draught fans and continuous water circulation are arranged for efficient heat rejection. Every seven days it is required to replenish 5000 to 6000 liter of water in a tank with ground water to compensate consumption during evaporative cooling process. Elsewhere in the plant, the heating demand for milk processing is met by a coal fired tube-in-tube boiler of 3 Ton capacity. Boiler is employed to generate high pressure steam (7.50 Kg/cm^2) for pasteurization, milk heating & processing and CIP. In order to increase the thermo-economic efficiency of the boiler, the same is equipped with an air pre-heater (APH), a water pre-heater (WPH), a dust collector and a wet scrubber as shown in Figure 1. After passing through the dust collector, the WPH and wet scrubber, the cleaned & low heat content air is exhausted through a chimney.

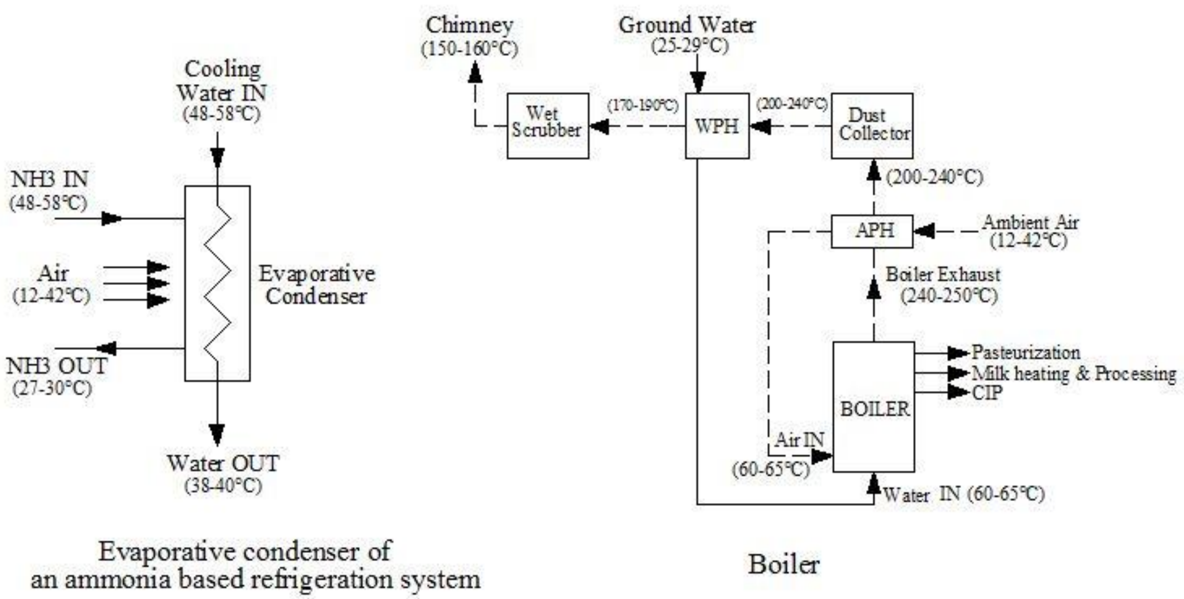

Figure 1: Schematic of existing heating and cooling system

2.1 Heating and cooling demand in the plant

The boiler meets about 183116 MJ of heating demand per day in the plant. Where about 36 TR of cooling demand per day is met by electric power supply. Heating demand is in milk pasteurization, milk condensing, milk drying, clarified butter (ghee) processing and CIP. Cooling demand is in milk chilling, milk pasteurization, product processing, prepack milk pouch filling, milk cold storage and powder milk production as shown in Figure 2.

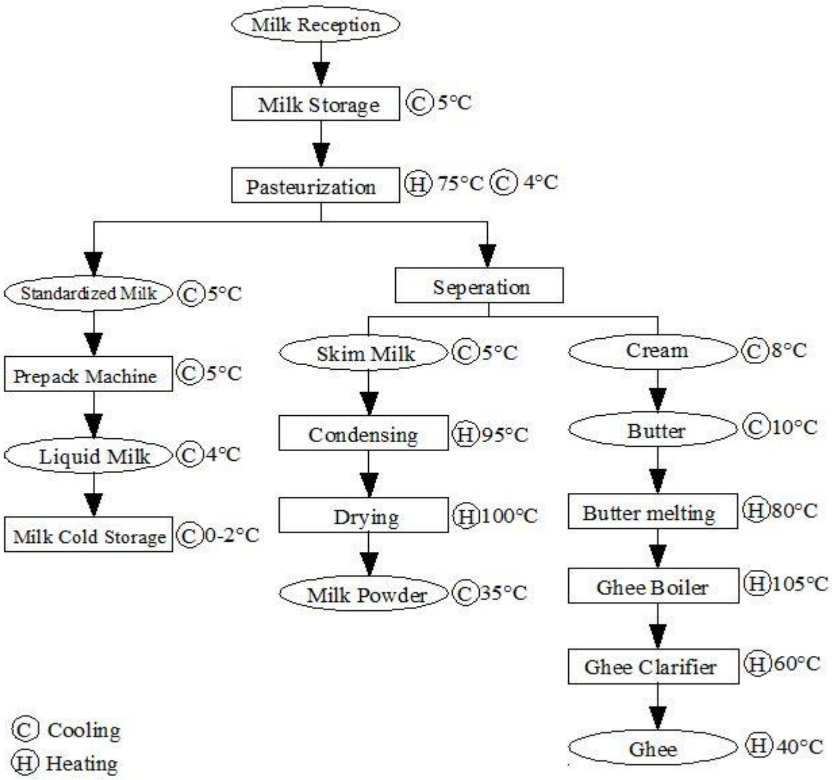

Figure 2: Various operations carried out in milk processing

Pasteurization is a process, which require both cooling and heating, where milk temperature is raised to minimum 71.5°C in 14 seconds, held for about 15 seconds and thereafter, chilled to 4°C in 12 seconds. The purpose of pasteurization of milk is to destroy pathogens present and thereby increase shelf.

2.2 Energy consumption

Methodology adopted for measuring current operational energy consumption during various processes is shown in Figure 3 and instrumentation used for the same is tabulated in Table 1.

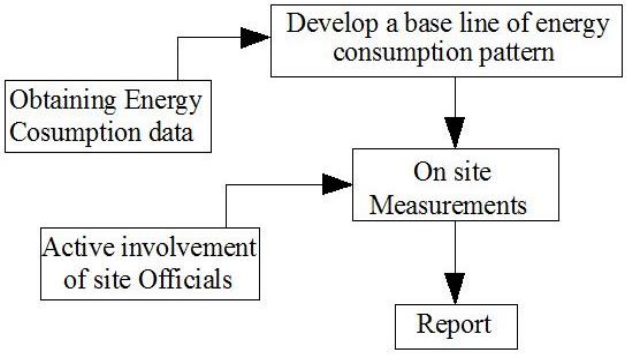

Figure 3: Energy consumption measurement

Due permission and support from officials/supervisors is taken to collect information about the various processes, milk load distribution within the plant and operational data. The data was analyzed to arrive at a base line energy consumption pattern and to identify the energy usage pattern and losses in the system. Measurements and monitoring is carried out with appropriate instruments including continuous and time lapsed recording.

Table 1: Instruments used for measurements

Instrument	Parameter	Measuring Range	Accuracy
	Oxygen	0 to 21%	± 0.2%
Combustion analyzer	Carbon monoxide	0 to 4000 ppm	± 20 ppm (< 400 ppm) ± 5% (> 400 ppm)
	Temperature	0 to 600°C	± 0.3%
Anemometer	Air velocity	0.5 to 89 miles/hr	± 3%
Digital pressure meter	Pressure	0 to 350 mbar	± 0.2%
Surface temp. indicator	Temperature	-50°C to 450°C	0.5°C

Figure 4 shows monthly averaged variation of maximum heat rejected from condenser of the ammonia based refrigeration system, coal consumption variation in the boiler and the variation in average milk handling, months 1 to 12 represents January to December.

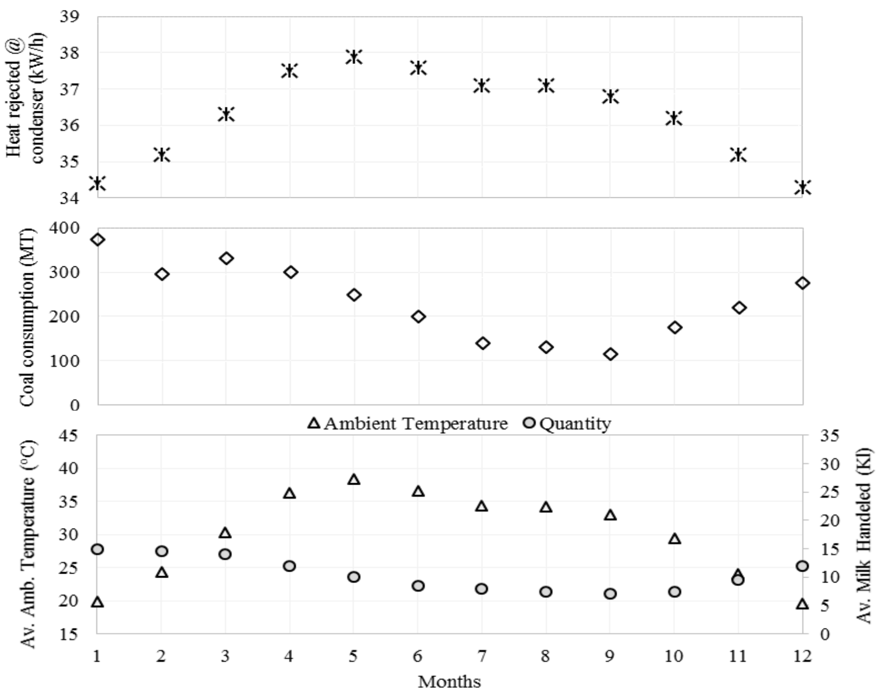

Figure 4: Heat available, coal consumed, average ambient temperature and milk handling (year 2015)

The heating demand at various processes within the milk plant is handling by steam from boiler which uses ground water as boilers feed available in temperature range 25 to 29°C round the year. The boiler related information required for boiler efficiency calculation is tabulated in Table 2.

The daily average flow rate of water for boiler facility is 3.5-4 m^3/h. The boiler tank water holding capacity is 11 m^3. Approximately, 4.5 liters of water is supplied for per kg of coal consumption.

Table 2: Boiler data

Variable	Unit	Value/Range
Fuel		Coal
Flue gas temperature before APH	°C	294
Flue gas temperature after APH	°C	208
Ambient temperature (Daily averaged)	°C	15 to 48
Calorific value of fuel	Kcal/Kg	3500
Average Oxygen percentage in flue gases	%	9.7
Operating steam pressure	Kg/cm^2	7.5
Sensible heat loss		
Excess air	%	86
Theoretical air required to burn 1 Kg of fuel	Kg/Kg of fuel	4.86
Total air supplied	Kg/Kg of fuel	9.04
Weight of flue gas	Kcal/Kg °C	10.04
Specific heat of flue gases	Kcal/Kg of fuel	603
Heat loss in flue gases	%	17.2
Heat loss due to evaporation of moisture in fuel		
Moisture in fuel	Kg/Kg of fuel	0.31
Specific heat	Kcal/Kg of fuel	0.45
Heat loss due to moisture in fuel	%	6.2
Heat loss due to evaporation of water formed due to hydrogen in fuel		
Hydrogen in fuel	Kg/Kg of fuel	0.02
Specific heat	Kcal/Kg of fuel	0.45
Heat loss due to hydrogen in fuel	%	3.6
Other losses (radiation losses, blow down, heat losses due to unburnt carbon in ash etc.)	%	3
Total losses	%	30
Boiler efficiency	%	70

2.3 Incorporation of trans-critical CO_2 heat pump system

Figure 5 shows the proposed trans-critical CO_2 heat pump system, coupled with existing ammonia based refrigeration and boiler system. The trans-critical CO_2 heat pump meets simultaneous heating and cooling demands. The evaporator of the heat pump system takes up heat from the ammonia cycle and boiler feed water is preheated utilizing the heat rejected by the gas cooler.

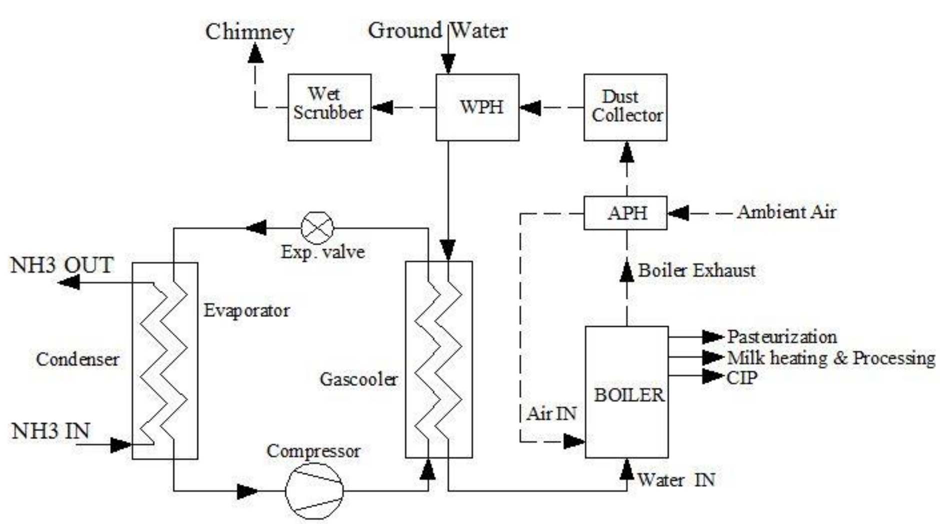

Figure 5: Schematic of proposed trans-critical CO_2 heat pump system

Figure 6 shows representative P-h plot of the transcritical CO_2 heat pump system introduced replacing the evaporative cooling arrangement.

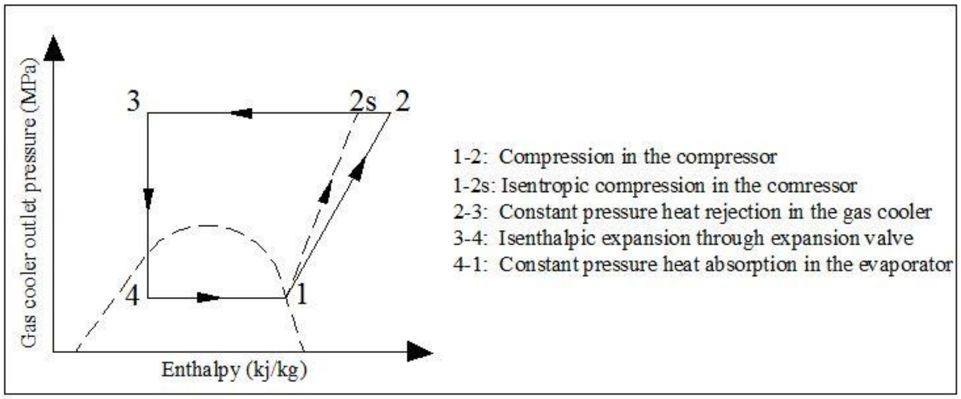

Figure 6: P-h plot of proposed trans-critical CO_2 heat pump system

As per the required cooling and heating demand in the milk refrigeration plant, heat pump system parameters such as discharge pressure, suction temperature, gascooler outlet temperature, etc. are to be optimized for maximum COP.

3. MODEL DESCRIPTION

Steady flow energy equation, mass balance and exergy balance equations are used to build a simulated model for analysis. Range and values of the variables/constants used in the study are tabulated in Table 3.

Table 3: Parameters for trans-critical CO_2 heat pump system

Parameter	Value/Range
Evaporator temperature	20°C
Gascooler outlet temperature	35 to 39°C
Gascooler outlet pressure	8 to 12 MPa
Ground water temperature	25°C to 29°C
Isentropic efficiency of compressor	70%
Approach temperature	10°C

The following assumptions are made for the simulation:

- Pressure drop in pipes, gas cooler and evaporator are negligible.
- Heat losses to the environment from gas cooler and evaporator are negligible.

For the simulation, compressor work is computed using Eq. 1:

$$W_{comp} = m(h_2 - h_1) \tag{1}$$

Isentropic efficiency of compressors is computed using Eq. 2:

$$\eta_{is} = \left(\frac{h_2 - h_1}{h_{2s} - h_1}\right) \tag{2}$$

Trans-critical CO_2 heat pump systems cooling & heating COP are computed using Eq. 3 & 4:

$$COP_{cooling} = \frac{h_2 - h_4}{h_2 - h_1} \quad (3)$$

$$COP_{heating} = \frac{h_2 - h_3}{h_2 - h_1} \quad (4)$$

The model is simulated in MATLAB platform and the refrigerant properties are obtained from REFPROP version 9.0.

4. RESULTS AND DISCUSSION

4.1 Variation with gas cooler outlet pressure

Figure 7 shows variation of cooling COP and heating COP with gas cooler outlet pressure at various gascooler outlet temperatures.

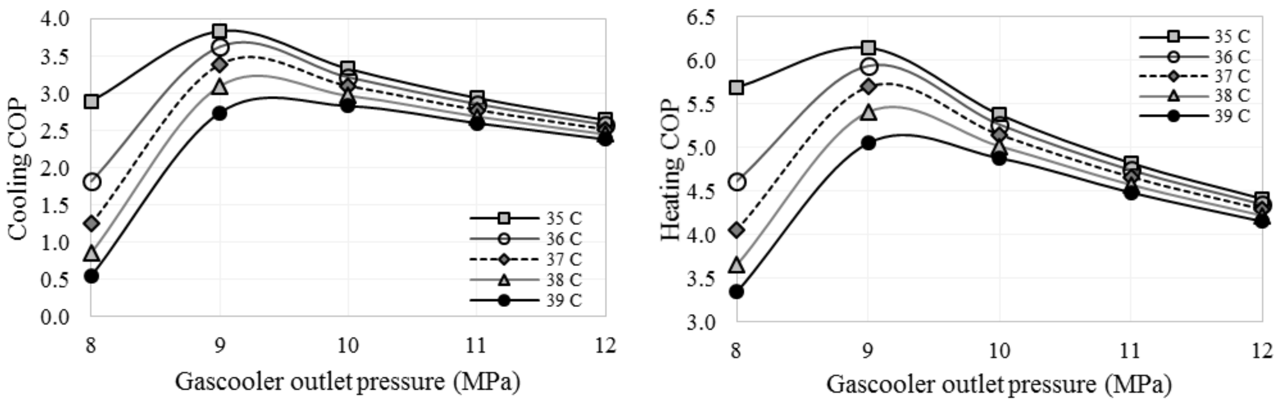

Figure 7: Variation of cooling COP and heating COP with gas cooler outlet pressure at various gascooler outlet temperature

Observations made from the study of variation of cooling and heating COP with gascooler outlet temperature are following:

- A steady decrease in cooling and heating COP is observed with increasing gascooler outlet pressure across various gascooler outlet temperatures beyond the maxima at around 9 MPa. This can be attributed to the fact that increase in gas cooler outlet pressure leads to increase in exergy loss from the system components resulting into reduction of COP.
- With decrease in gascooler outlet temperature, the systems COP increases, as the pressure difference between gascooler pressure and evaporator decreases.

4.2 Maximum heat available

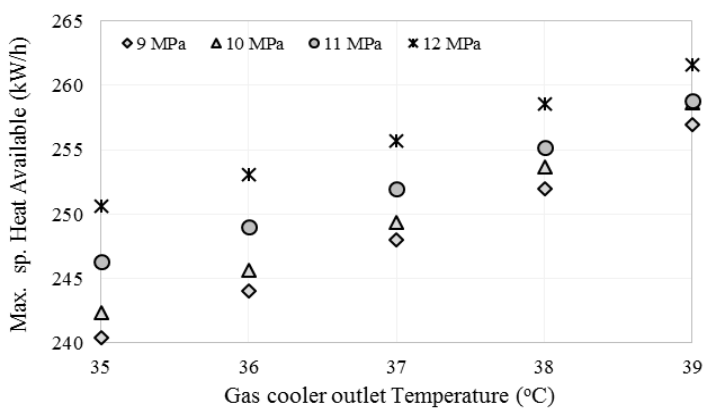

Figure 8: Variation of max. specific heat available at gascooler with various gascooler outlet temperature

The maximum heat available for feed water preheating at the various gascooler outlet pressure at various gascooler outlet temperature are shown in Figure 8. As expected, heat transfer to boiler feed water increases with increase in gas cooler outlet temperature.

4.3 Impact analysis

Energy consumption measurement is carried out to identify potential cost saving due to the introduction of heat pump in existing system and is tabulated in Table 4. Total reduction rate (RR) of electricity consumed & CO_2 emission are computed by using Eq. 5.

$$Reduction\_rate = \left(\frac{Current - proposed}{Current}\right) * 100 \qquad (5)$$

Table 4: Energy consumption using current system and proposed trans-critical CO_2 heat pump system

			Unit	Current	Proposed	RR
ENERGY CONSUMPTION	ELECT.	Heat pump elect. consumption	kW h^{-1}		24	
		Cooling capacity	kW	37	37	
		Chiller	COP	2.3	2.3	
		Chiller electricity consumption	kW h^{-1}	16.3	16.3	
		Total electricity consumption	kW h^{-1}	16.3	40.3	
	COAL	Boiler heat capacity	kW	59	59	
		Calorific value of coal	Kcal kg^{-1}	3500	3500	
		Density of coal	Kg l^{-1}	0.866	0.866	
		Effective utilization ratio	%	0.50`	0.50`	
		Consumption of coal	Kg h^{-1}	183.3─629	91.5─314.5	
		Water for evaporative cooling	Liters	5000		
ANNUAL ENERGY CONSUMPTION	ELECT.	Consumption of electricity	MWh	101	249	
		CO_2 emission	t-CO_2 kWh^{-1}	0.93	0.93	
		Total CO_2 emission	t-CO_2	93930	231570	
		Energy cost	Rs kW^{-1} h^{-1}	8.00	8.00	
		Total energy cost	Rs	808000	1992000	
	COAL	Coal consumption	Tones	2807	1402	
		CO_2 emission	t-CO_2 Kg^{-1}	2.71	2.71	
		Total CO_2 emission	t-CO_2	7606970	3799420	
		Energy cost	Rs Kg^{-1}	7.86	7.86	
		Total energy cost	Rs	22063020	11019720	
		Total CO_2 emission	t-CO_2	7700900	4030990	47.6%
		Total Energy cost	Rs	22871020	13011720	43.1%
		Annual of cost reduction	Rs		9859300	

From Table 4, we see that the total electricity consumption in the proposed system has increased due to introduction of an additional compressor for the trans-critical CO_2 heat pump system. Heat rejection from gascooler is used to heat the boiler feed water which reduces coal consumption resulting in cost saving on fuel. In the current system, daily water supply to the boiler facility is 7.3─10.9 m^3 and the available heat can be used to preheat the water upto 80°C before feeding into the boiler. The total CO_2 emission is also reduced by about 47.6% because of overall reduction in coal consumption and net energy consumption cost is reduces by about 43.1%. Further there is ground water saving as reported earlier due to elimination of evaporative cooling.

5. CONCLUSIONS

In order to increase the efficiency of a milk processing & refrigeration plant by reducing coal consumption, ground water usage and heat rejection, a trans-critical CO_2 heat pump system is introduced that utilizes the rejected heat from the ammonia based refrigeration system to preheat the boiler feed water. The total energy saving in the terms of cost & its annual impact on the system is calculated. Further, reduction in total CO_2 emission is also contrasted.

The following conclusions are drawn from this study:

- Approximately 37 KW h^{-1} heat is recovered by employing trans-critical heat pump system.
- Approximately 5000 L of ground water per week, currently consumed for evaporative cooling, is saved.
- Total electricity consumption increases by about 50%.
- Overall coal consumption is reducing approximately by 48%.
- Total reduction rate in CO_2 emission and cost of energy is approximately 47.6% and 43.1% respectively.

NOMENCLATURE

H,h	Enthalpy	(kJ Kg^{-1})
S,s	Entropy	(kJ Kg^{-1} K^{-1})
W	Work done	(kW h^{-1})
m_r	Mass flow rate	(kg s^{-1})
Q	Total heat transfer	(kJ s^{-1})
is	Isentropic	
C,comp	Compressor	
COP	Coefficient of performance	
CIP	Clean in place	
HSD	High speed diesel	
FAO	Food and Agriculture Organization	
CO_2	Carbon dioxide	
TR	Tones of Refrigeration	
C	Compressor	
E	Electricity	
T	Tones	

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