Exergy and thermoeconomic analysis of cream pasteurisation plant

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Abstract

Cream is a milk derivative comparatively rich in fat, present in the form of emulsion of fat in skimmed milk, and acquired by physical extraction from raw milk with the help of centrifugal separator. The cream with variable fat content (10–40%) is commonly employed as an ingredient to traditional or modern desserts. It is also used in the production of value-added milk products such as butter and ghee apart from regular cooking applications. The pasteurisation, being an important safety requirement of milk food products, is usually materialised by heating the milk cream at a temperature of 90 °C for a period of one second. In the current work, thermodynamic and thermoeconomic derivatives in combination with all available constraints have been determined for high temperature short-time cream pasteurisation plant. The energy and exergy efficiency of cream pasteurisation plant was determined to be 86.88% and 66.11%, respectively. The cumulative value of energy destruction and exergy demolition in subunits of cream pasteurisation plant was estimated to be 93.88 kW and 11.39 kW, respectively, which mainly ascribed to complete enzymatic denaturation of fluid cream. The overall operating cost rate of complete cream pasteurisation plant was calculated as 1649.10 Rs./H, 22.02% portion of which was associated with electrical energy consumption. Further, the cost rate of exergy degradation for chilling and cooling activities was reported as 617.57 Rs./H and 357.55 Rs./H, respectively. The exergoeconomic factors of heating (14.75%) and chilling activity (0.82%) articulated that capital investment was dominant in the former while thermal degradations were enunciated most flagrant in latter.

Keywords Energy efficiency · Exergy efficiency · Exergoeconomic analysis · Cream pasteurisation plant

List of symbols

AC	Annual cost of component (Rs.)
$\dot{C}$	Cost flow rate (Rs. H^{-1})
c	Exergetic cost (Rs. MJ^{-1})
$c_{f,\,k}$	Unit exergetic cost of fuel (Rs. MJ^{-1})
$c_{p,\,k}$	Unit exergetic cost of product (Rs. MJ^{-1})
c_p	Specific heat (kJ kg^{-1} K^{-1})
CRF	Capital recovery factor
$D_{D,\,k}$	Cost rate of exergy destruction (Rs. H^{-1})
$\dot{E}$	Energy (kJ s^{-1})
$\dot{EL}$	Energy loss rate (kW)
$E_{\beta,\,k}$	Relative energy destruction ratio (%)
$Ex_{\beta,\,k}$	Relative exergy destruction ratio (%)
$E_{F,\,k}$	Energetic factor (%)
$Ex_{F,\,k}$	Exergetic factor (%)
ex	Specific exergy (kJ kg^{-1})
$\dot{Ex}$	Exergy rate (kW)
$\dot{Ex}_D$	Exergy destruction rate (kW)
E_{IP}	Energy improvement potential (kW)
Ex_{IP}	Exergy improvement potential (kW)
f	Exergoeconomic factor of component
h	Specific enthalpy (kJ kg^{-1})
H	Hour
I	Interest rate (%)
J	Ratio of salvage value
$\dot{m}$	Mass flow rate (kg s^{-1})
MF	Milk fat
PEC	Purchase equipment cost (Rs.)

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PWF	Present worth factor
PW	Present worth of component (Rs.)
r	Percentage relative cost difference (%)
Rs. MJ^{-1}	Rupees per mega-joule
T	Temperature (K)
s	Specific entropy (kJ kg^{-1} K^{-1})
S	Entropy (kJ K^{-1})
S	Salvage value (Rs.)
SI	Sustainability index
TCI	Total cost of investment (Rs.)
TOCR	Total operating cost rate (Rs. H^{-1})
TPD	Tons per day
v	Specific volume (m^3 kg^{-1})
W	Work rate (kW)
$\dot{Z}_T$	Levelised cost rate associated with capital investment and operation and maintenance cost (Rs. H^{-1})
$\dot{Z}_{CI}$	Levelised cost rate associated with capital investment (Rs. H^{-1})
$\dot{Z}_{OM}$	Levelised cost rate associated with operation and maintenance cost (Rs. H^{-1})
HTST	High temperature short time

Greek letters

R	Universal gas constant (8.314 kJ mol^{-1} K^{-1})
ρ	Density (kg m^{-3})
η	Energy efficiency (%)
Ψ	Exergy efficiency (%)
0	Dead state
€	Euro
Rs.	Rupees (Indian currency)

Subscripts

BT	Balance tank
CF	Condenser and fan combination
CHS	Chilling section
CS	Cooling section
HS	Heating section
HE	Heat exchanger
P1	Pump-1
P2	Pump-2
P3	Pump-3
P4	Pump-4
P5	Pump-5
RS	Regeneration section
ST	Storage tank
WT	Water tank
k	Any component
In	Inlet
Out	Outlet
T	Total

Introduction

The FAO statistics revealed that the global annual milk production was estimated to be 819 MT in the year 2016, 19.57% of which was produced by India alone. India's share in global import and export trade of dairy products was weighed up to be 0.19% and 0.68% of its global annual counterparts [1]. India's 4% annual growth pace propelled the engine of global milk trade from 5% in 1970 to 17.4% in 2012 despite the non-conducive environment (hot and humid) for milk production and processing along with limited automation of this industry. As far as Indian production scenario of various dairy products is concerned, the contribution of milk cream production is reported to be least (1%), whereas the second highest share of percentage production is maintained by ghee production (28%) after fluid milk production (44%) [2–4].

The improper demand—supply equation of energy, particularly in the developing nations—forces the processing units to install their own heavy duty thermal utility and electrical energy generation systems which would inevitably count on conventional fuel supply for execution of mechanical and non-mechanical activities of processing plants. Since the cost–quality matrix has its direct linkage with consumption and degradation, the resource quantification with the help of advanced thermodynamic and thermoeconomic tool has become highly indispensable [5–7]. Fadare et al. [8] evaluated exergy gauge to estimate processing capabilities of malt drink processing units. The packing house activity was reported to be least efficient, and the average process energy intensity was calculated to be 261,630 kJ hl^{-1}. Similarly, Nasiri et al. [9] revealed the contribution of steam generator (57%) in a long-life ultra-filtrated cheese manufacturing plant. They also estimated the average specific exergy deterioration to be 2330.42 kJ kg^{-1}. Thermodynamic evaluation of double effect tomato paste plant was carried out by Mojarab et al. [10]. The exergy deficiency of the first and second evaporative processes was computed to be 34.67% and 43.40%, respectively. The consumption of specific exergy in the said plant was calculated to be 16830 kJ kg^{-1} which was obtained by processing of actual operational data. Similarly, Dowlati et al. [11] portrayed variety of exergy derivatives for an ice cream manufacturing division situated in Tehran Province. The analysis diagnosed the frail and firm exergetic features of subcomponents of the plant, e.g. most deficient performance was captured in case of ice cream production line followed by steam generation and refrigeration while overall institutional exergy deficiency was figured out to be very high (97.85%) in magnitude. Furthermore, Genc et al. [12] generated some concrete outcomes by instituting exergy scale for red wine

production unit located in Tehran, Iran. The subunits of the plant were ranked according to magnitude of exergy degradation, i.e. least amount of reversibility was confirmed in open fermenter (3.05%) whereas a meagre proportion of the same was assessed in case of plate and frame filter (0.53%) and crusher destemmer (0.084%). The overall exergy and energy deficiency of the plant was measured up to be 58.20% and 42.80%, respectively. In continuation of same exercise, Pandey et al. [13] chose North Indian climatic region for assessment of thermal derivatives, e.g. energy and exergy efficiency of multi-crystalline solar photovoltaic module for different months of a year. The aforementioned parameters registered the highest and lowest values in the months of February and December, respectively. Moreover, amount of availability content and efficiency thereof gauged to be comparatively on higher side in the morning time.

In another similar kind of research work, Pelvan et al. [14] assessed the sustainability characteristics of tea production process in combination with waste potential of the plant; in terms of indices such as cumulative degree of perfection (COD), cumulative carbon dioxide emission (CCO2E) and renewability indicator (RI). The study pointed towards significant improvement in exergetic behaviour of plant, given the condition when waste of subjected to valorisation. In another similar kind of research work, Basaran et al. [15] discussed the case of tomato pasteurisation by involving induction heating, wherein the system consumed 40.98 kW of high grade energy for materialising the aforementioned activity, compared to electrical energy-assisted pasteurisation in which exergy consumption was 26% higher than that of induction heating counterpart. Also, exergy efficiency of induction-based sterilisation was reported as 46.56%. Similarly, Singh et al. [16] calculated exergy and exergoeconomic aspects of ultra-high temperature milk pasteurisation. The specific exergy destruction, improvement potential and overall cost rate of exergetic degradation were identified to be 219.23 kJ kg^{-1}, 130.60 kJ kg^{-1} and 8082.50 € H^{-1}, respectively. The specific manufacturing cost of UHT processed milk was ascertained to be 1.355 € kg^{-1}. Further, existence of some works [16–21] enumerated the significance of exergetic approach in assessment of solar energy-based applications such as heat pump operation, mobile air conditioning, food baking, water heating and sterilisation of liquid milk products. In prolongation to similar approach, Kwak et al. [22] unified exergy and cost balance equations to evolve the highest unit exergy cost rate of combustor and gas compressor. However, total cost of exergy degradation was enumerated to be 12.78 \$ h^{-1} at 100% loading condition. On a similar note, Tsatsaronis [23] generated the circuitous information related to the exergoeconomic behaviour of thermal system which otherwise could never be dredged up by conventional gauges of economic analysis. Interconnection between exergy degradation and their monetary equivalence was studied by Lazzaretto and Tsatsaronis [24]. In this work, cost balance equations were solved in assistance with auxiliary equations to procure monetary figures of exergy demolition in a process flow structure.

The cost break-up of various subunits in consolidation with thermodynamic specifications of plant would induce a rational spectrum of losses for a nearly optimal mechanical system. A mathematical formulation is related to energy, exergy and exergoeconomic evaluations of large-scale cement plant and their subsequent integration with actual performance data to obtain the cost-oriented implications and repercussions in combination with thermodynamic derivatives by Atmaca and Yumrutas [25, 26]. The opportunity of heat integration and waste heat recovery apart from productivity improvement, enhancement in overall sustainability of plant, had not been comprehensively reported in previous works [27–33]. Moreover, the conventional approach of thermodynamic or economic evaluation of any thermal system had not been given broad coverage to explore economic or energy savings prospects, particularly for the energy system wherein aforementioned objectives are not perfectly highlighted [34–39].

Despite having a several numbers of research work related to exergy and exergoeconomic analysis for different types of food processing and production units, there still exists great scope in qualitative and quantitative judgement of exergy destruction and improvement potentials in production and processing activities of variety of traditional and modern value-added dairy products, such as whipped cream, butter milk and ghee. In view of high worth of specific thermal and electrical exergy requirements in dairy product processing divisions, the exact coverage of capital consumption or exergy destruction in consideration with thermal and monetary constraints has become a serious issue, the detailed idea of which would assist plant designer or planners to mature blueprint for accomplishment of maximum attainable thermal and thermoeconomic performances of plant. The present research work provides an exhaustive judgement of thermoeconomic and thermodynamic derivatives such as cost equivalent of exergy destruction, exergy efficiency and specific exergy destruction. In addition to above, percentage measure of cost difference in relation to exergy values of flow streams, thermoeconomic indices, comprehensive operational cost rate will provide a sound basis for genuine prediction of thermoeconomic attributes of a factory scale cream sterilisation plant of milk food industry in India.

Plant description and methodology

Plant description

The high temperature short-time cream pasteurisation line of the dairy processing concern is represented in Fig. 1. It consists of one regeneration section, one heating section, one cooling and one chilling section. Primarily plate heat exchangers are involved for the purpose of executing above-mentioned activities of cream pasteurisation process.

The cream with 40% fat content is first passed through the regeneration section where a temperature rise of 24 °C is achieved. The pump-3 supplies the cream to heating section where another significant temperature rise is obtained. The high temperature cream is then passed again through the regeneration section where necessary heat exchange between hot and cold fluids takes place. In the last part of travel, cream flows through cooling section; the cooling activity is realised by cold water flowing in the opposite line. The temperature of hot water is brought down by condenser and fan combination which works in conjunction with cooling section of cream pasteuriser.

Finally, the chilling of cream is materialised by flowing chilled water in the chilling section of the pasteuriser. There is one separate section for hot water generation which consists of shell and coil heat exchanger, water tank and a feed water pump. There are some redundant units meant for the purpose of long- and short-time storage of the cream.
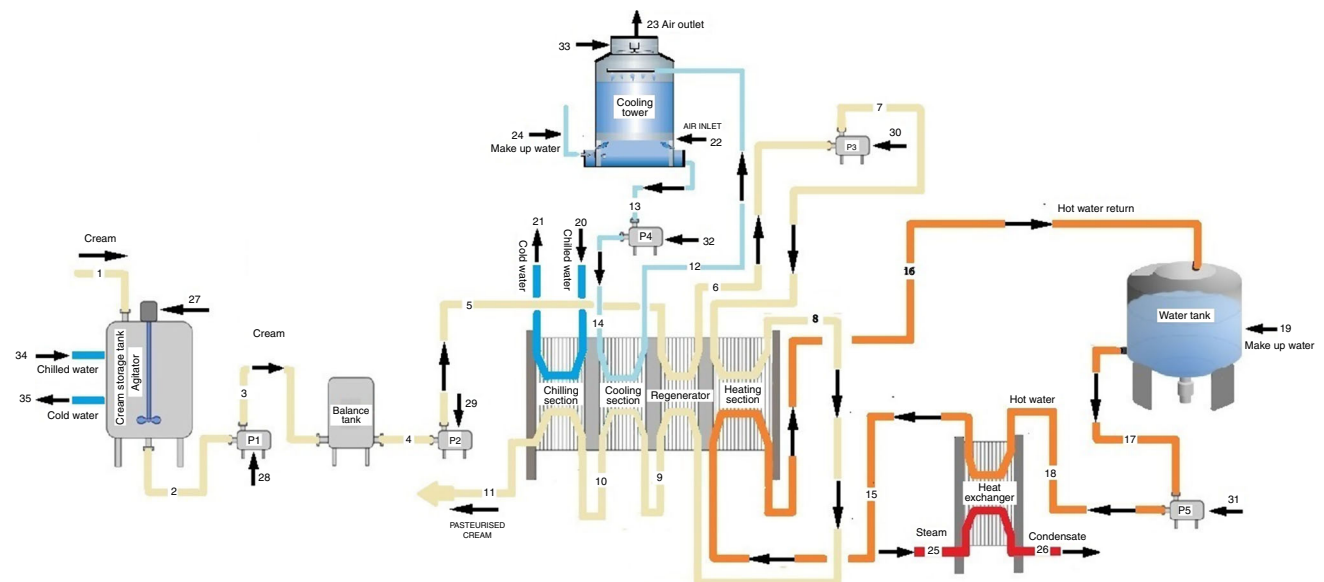
Pasteurisation

Pasteurisation is described as a process of thermal treatment administered for milk, cream or any other fluid with the goal of optimising health safety of human beings. The fluid products are prone to pathogenic disorder; therefore, it becomes highly imperative to provide suitable and sufficient heat treatment to them. In addition to the aforementioned target of pasteurisation, the secondary foremost idea behind thermal nursing is to bring reduction in any changes related to its chemical, physical and organoleptic features along with an achievement of optimum rise in the shelf life of final products by systematically phasing out the dangerous bacteria and enzymes [2].

Usually phosphatase or peroxide tests are instituted for this purpose, and in particular, they are employed for the milk food products having fat content less than 8%. But, however, in order to pasteurise the cream with different fat contents or to have strict control on enzymatic activities, the high-fat commodities are commonly pasteurised at 90 °C with different time residency requirements. Basically in order to curb the reactivation of enzymes immediately after pasteurisation, a thermal treatment of fairly strong strength is highly essential. The phosphatase and peroxide are the two main enzymes which get absolutely crushed or killed in high temperature treatment of milk and cream, respectively [4].

The pasteurisation of milk and cream is highly mandatory activity, as the stability and safety of value-added products such as butter, ghee and cheese are of utmost important. In order to secure negative results of peroxide test for the high-fat (10–48%) cream, there must be some

Fig. 1 Schematics diagram of milk cream pasteurisation plant

Table 1 Types of temperature–time combinations for cream pasteurisation process [2]

S. no.	Type of cream pasteurisation	Temperature–time combination
1	HTST method with 10–20% fat	65 °C for 30 min
2	HTST method with > 20% fat	75 °C for 15 min
3	HTST method with > 40% fat	90 °C for 1 s

optimum time and temperature coalitions for variety of fat compositions. Typical minimum time–temperature associations required to exhibit a negative phosphatase test are given in Table 1.

The whole milk is provided with mild heat treatment so that an environment conducive to cream separation could be created. The cream separation activity is usually performed at a temperature range of 51–55 °C. Milk is usually standardised after the fat separation, i.e. some amount of fat is added back into the milk to conform to the national or international standard of milk pasteurisation. The surplus cream is usually pasteurised in a cream pasteuriser before being processed for manufacturing of value-added products. The factors such as water activity, temperature, oxygen, osmotic pressure and pH value of cream have significant impact upon bacterial ballooning.

The magnification of pathogenic convulsion is usually accompanied by conducive thermal conditions. There exist an optimum temperature and time combination which would restrict or crush the imminent bacterial advancement. The shelf life of cream is another important requirement. Amongst the aforementioned methods of food preservations, the thermal nursing is the most viable and feasible solution of having an enhanced shelf life of food products.

Since the other specified techniques involve different kinds of mechanical arrangement, thus the product pasteurisation could be easily achieved by a food pasteuriser for variety of liquid food items. The intense exposure to fluid items creates necessary lethal effect on the microorganisms. The HTST techniques are meant for preservation of milk or cream for the specified period of time and application. However, there are several other techniques for achievement of extended shelf life (ESL) of the milk food items. The ultra-high temperature pasteurisation of milk and its value-added products has become very common to secure its tasteful and nutritional characteristics to some extent apart from extension of its shelf life for sufficient number of days. The discussion entails the fact that in order to process any milk food item, pasteurisation is most important activity without which safety, stability and longevity of products could not be ensured [11, 27, 40]. The pasteurisation of milk cream involves successive regeneration, heating, cooling and chilling.

The fluid regeneration is accompanied by simultaneous heating and cooling by the single fluid, so that heat content of hot fluid could be utilised to heat up low temperature fluid. Before execution of cream pasteurisation, the cream separation is the integral part of HTST milk pasteurisation process. The cream is extracted out of the whole milk by the use of cream separator which purely uses centrifugal force for materialisation of this activity.

Methodology

In order to evaluate the cream pasteurisation plant on exergoeconomic and thermodynamic platforms, the necessary technical details were obtained from a nearby Verka Milk Plant, Mohali, located few hundred kilometres towards north from national capital of India, which has a cream handling capacity of 20000 kg per day. The technical information instituted for the current assessment was observed and recorded by the technical executives of the plant for one year continuously. The following assumptions are assisted in formulation of thermodynamic background of current analysis as:

(a) The plant and its subdivisions remain steady under all operational conditions.

(b) The magnitudes of different forms of energy, e.g. kinetic or potential, were ignored mainly due to their minimal subscription [40].

(c) The reference state coordinates for thermal analysis are given as T_0: 298.15 K and P_0: 101.325 kPa.

(d) The contribution of crud development in exergetic degradation was negligible.

(e) The variation in reference state temperature was disregarded.

(f) The physical significance of fat formation exergy towards overall thermodynamic performance was disregarded [40].

Thermodynamic analysis

There are two fundamental propositions of thermal analysis which individually generate energetic and exergetic information of energy system. The exergy principle focuses upon unearthing the information related to energy degradation during product processing which could not be procured by first law of thermodynamics. Thus, it could be clearly understood that second law matures the plant

planner from the view point of location and identification of domains of thermal or electrical exergy destruction or consumption along with probable improvement by simultaneous retrofitting of plant.

Energy and exergy analysis

The mass balance equation employed for current study is given as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

The subscripts 'in' and 'out' stand for input and output, respectively.

The thermal equilibrium equation is given by:

$$\dot{Q}_{net,in} - \dot{W}_{net,out} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{2}$$

The first and second law performances are quantified by the following equations as:

$$\eta = \sum \frac{\dot{E}_{out}}{\dot{E}_{in}} \times 100 \tag{3}$$

$$\psi = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} \times 100 \tag{4}$$

The general exergy demolition equation is given by:

$$\dot{Ex}_{in} - \dot{Ex}_{out} = \sum \dot{Ex}_D \tag{5}$$

The equation concerning calculation of magnitudes of physical exergy rates at all the states of cream processing plants is given as follows:

$$\dot{Ex}_{ph} = \dot{m}\left[c_P\left(T - T_0 - T_0\left(\ln\frac{T}{T_0}\right)\right) + v(P - P_0)\right] \tag{6}$$

Table 2 provides thermodynamic framework for all the subunits of the plant.

Further, Table 3 provides mathematical formulations for each of the constituents of the plant in context of aforementioned thermodynamic background.

Exergoeconomic analysis

In order to calculate basic quantities such as hourly levelised cost rate of capital investment cost, hourly levelised cost rate of operational and maintenance activities and the total levelised cost rate of constituents of cream pasteurisation plant, the purchase equipment cost of subunits and associated operational cum maintenance expenses are procured from information supplied by supplier in its quotation and maintenance section of plant, respectively. The specific exergy costing method (SPECO), being the tool required for exergoeconomic appraisement, involves

Table 2 Key thermodynamic factors considered for present analysis [25, 26]

S. no.	Name of the factor associated with energetic evaluation	
1	Energy efficiency	$\eta = \frac{\dot{E}_{out,k}}{\dot{E}_{in,k}} \times 100$
2	Energy destruction	$\dot{E}_{L,k} = \dot{E}_{in,k} - \dot{E}_{out,k}$
3	Energy improvement potential	$\dot{E}_{IP,k} = (1 - \eta_I) \times \dot{E}_{L,k}$
4	Relative energy destruction ratio	$E_{\beta,k} = \frac{\dot{E}_{L,k}}{\sum \dot{E}_{L,k}} \times 100$
5	Energetic factor	$E_{f,k} = \frac{\dot{E}_{in,k}}{\sum \dot{E}_{in,k}} \times 100$
6	Energy efficiency of plant	$\eta_p = \frac{\sum \dot{E}_{out,k}}{\sum \dot{E}_{in,k}} \times 100$

S. no.	Name of the factor associated with exergetic evaluation	
1	Exergy efficiency	$\psi = \frac{\dot{Ex}_{out,k}}{\dot{Ex}_{in,k}} \times 100$
2	Exergy destruction	$\dot{Ex}_D = \dot{Ex}_{in} - \dot{Ex}_{out}$
3	Exergy improvement potential	$\dot{Ex}_{IP} = (1 - \psi) \times \dot{Ex}_D$
4	Relative irreversibility factor	$Ex_{\beta,k} = \frac{\dot{Ex}_{D,k}}{\sum \dot{Ex}_{D,T}} \times 100$
5	Exergetic factor	$Ex_{\Gamma,k} = \frac{\dot{Ex}_{in,k}}{\sum \dot{Ex}_{in,k}} \times 100$
6	Sustainability index	$SI = \frac{1}{1-\psi}$
7	Exergy efficiency of plant	$\Psi_p = \frac{\sum \dot{Ex}_{out,k}}{\sum \dot{Ex}_{in,k}} \times 100$

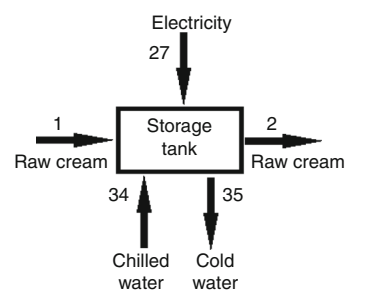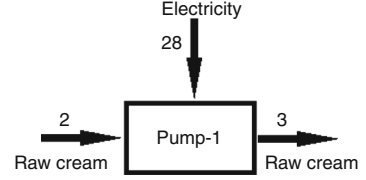**Table 3** Energetic and exergetic relations of key units of HTST cream pasteurisation plant
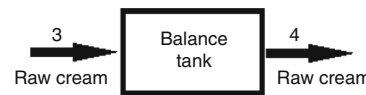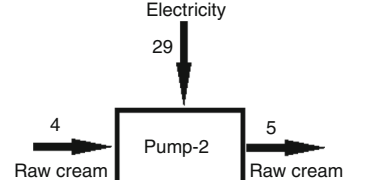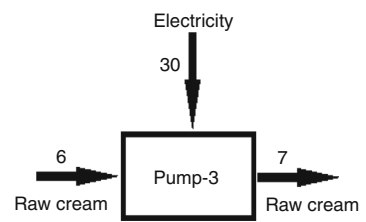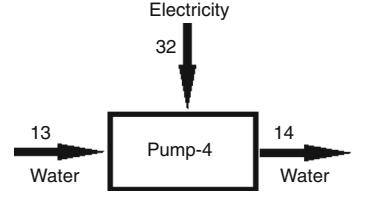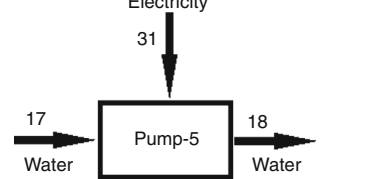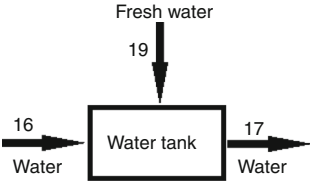
S. no.	Component	Energy and exergy relations
1	Electricity 27 → Storage tank; 1 Raw cream →, 2 → Raw cream; 34 ↑ Chilled water, 35 ↓ Cold water	$\dot{m}_1 = \dot{m}_2$ $\dot{E}_L = \dot{E}_1 + \dot{E}_{34} + W_{27} - \dot{E}_2 - \dot{E}_{35}$ $\dot{E}_D = \dot{Ex}_1 + \dot{Ex}_{34} + W_{27} - \dot{Ex}_2 - \dot{Ex}_{35}$ $\eta = \frac{\dot{E}_2 + \dot{E}_{35}}{\dot{E}_1 + W_{27} + \dot{E}_{34}} \times 100$ $\psi = \frac{\dot{Ex}_2 + \dot{Ex}_{35}}{\dot{Ex}_1 + W_{27} + \dot{Ex}_{34}} \times 100$
2	Electricity 28 → Pump-1; 2 Raw cream →, 3 → Raw cream	$\dot{m}_2 = \dot{m}_3$ $\dot{E}_L = \dot{E}_2 + W_{28} - \dot{E}_3$ $\dot{Ex}_D = \dot{Ex}_2 + W_{28} - \dot{Ex}_3$ $\eta = \frac{\dot{E}_3}{\dot{E}_2 + W_{28}} \times 100$ $\psi = \frac{\dot{E}_3 - \dot{E}_2}{W_{28}} \times 100$
3	3 Raw cream → Balance tank; 4 → Raw cream	$\dot{m}_3 = \dot{m}_4$ $\dot{E}_L = \dot{E}_3 - \dot{E}_4$ $\dot{Ex}_D = \dot{Ex}_3 - \dot{Ex}_4$ $\eta = \frac{\dot{E}_4}{\dot{E}_3} \times 100$ $\psi = \frac{\dot{Ex}_4}{\dot{Ex}_3} \times 100$
4	Electricity 29 → Pump-2; 4 Raw cream →, 5 → Raw cream	$\dot{m}_4 = \dot{m}_5$ $\dot{E}_L = \dot{E}_4 + W_{29} - \dot{E}_5$ $\dot{Ex}_D = \dot{Ex}_4 + W_{29} - \dot{Ex}_5$ $\eta = \frac{\dot{E}_5}{\dot{E}_4 + W_{29}} \times 100$ $\psi = \frac{\dot{Ex}_5 - \dot{Ex}_4}{W_{29}} \times 100$
5	Electricity 30 → Pump-3; 6 Raw cream →, 7 → Raw cream	$\dot{m}_4 = \dot{m}_5$ $\dot{E}_L = \dot{E}_6 + W_{30} - \dot{E}_7$ $\dot{Ex}_D = \dot{Ex}_6 + W_{30} - \dot{Ex}_7$ $\eta = \frac{\dot{E}_7}{\dot{E}_6 + W_{30}} \times 100$ $\psi = \frac{\dot{Ex}_7 - \dot{Ex}_6}{W_{30}} \times 100$
6	Electricity 32 → Pump-4; 13 Water →, 14 → Water	$\dot{m}_{13} = \dot{m}_{14}$ $\dot{E}_L = \dot{E}_{13} + W_{32} - \dot{E}_{14}$ $\dot{Ex}_D = \dot{Ex}_{13} + W_{32} - \dot{Ex}_{14}$ $\eta = \frac{\dot{E}_{14}}{\dot{E}_{13} + W_{32}} \times 100$ $\psi = \frac{\dot{Ex}_{14} - \dot{Ex}_{13}}{W_{32}} \times 100$
7	Electricity 31 → Pump-5; 17 Water →, 18 → Water	$\dot{m}_{17} = \dot{m}_{18}$ $\dot{E}_L = \dot{E}_{17} + W_{31} - \dot{E}_{18}$ $\dot{Ex}_D = \dot{Ex}_{17} + W_{31} - \dot{Ex}_{18}$ $\eta = \frac{\dot{E}_{18}}{\dot{E}_{17} + W_{31}} \times 100$ $\psi = \frac{\dot{Ex}_{18} - \dot{Ex}_{17}}{W_{31}} \times 100$

Table 3 (continued)

S. no.	Component	Energy and exergy relations
8	Cooling section (Water 12 in, Milk 9 in, Milk 10 out, Water 14 out)	$\dot{m}_9 + \dot{m}_{12} = \dot{m}_{10} + \dot{m}_{14}$ $\dot{E}_L = (\dot{E}_9 + \dot{E}_{12}) - (\dot{E}_{10} + \dot{E}_{14})$ $\dot{Ex}_D = (\dot{Ex}_9 + \dot{Ex}_{12}) - (\dot{Ex}_{10} + \dot{Ex}_{14})$ $\eta = \frac{\dot{E}_{10} + \dot{E}_{14}}{\dot{E}_9 + \dot{E}_{12}} \times 100$ $\psi = \frac{\dot{Ex}_{10} + \dot{Ex}_{14}}{\dot{Ex}_9 + \dot{Ex}_{12}} \times 100$
9	Regeneration section (Milk 8 in, Milk 5 in, Milk 9 out, Milk 6 out)	$\dot{m}_5 + \dot{m}_8 = \dot{m}_9 + \dot{m}_6$ $\dot{E}_L = (\dot{E}_5 + \dot{E}_8) - (\dot{E}_9 + \dot{E}_6)$ $\dot{Ex}_D = (\dot{Ex}_5 + \dot{Ex}_8) - (\dot{Ex}_9 + \dot{Ex}_6)$ $\eta = \frac{\dot{E}_9 + \dot{E}_6}{\dot{E}_5 + \dot{E}_8} \times 100$ $\psi = \frac{\dot{Ex}_9 + \dot{Ex}_6}{\dot{Ex}_5 + \dot{Ex}_8} \times 100$
10	Heating section (Hot water 15 in, Milk 7 in, Milk 8 out, Hot water 16 out)	$\dot{m}_7 + \dot{m}_{15} = \dot{m}_8 + \dot{m}_{16}$ $\dot{E}_L = (\dot{E}_7 + \dot{E}_{15}) - (\dot{E}_8 + \dot{E}_{16})$ $\dot{Ex}_D = (\dot{Ex}_7 + \dot{Ex}_{15}) - (\dot{Ex}_8 + \dot{Ex}_{16})$ $\eta = \frac{\dot{E}_7 + \dot{E}_{15}}{\dot{E}_8 + \dot{E}_{16}} \times 100$ $\psi = \frac{\dot{Ex}_7 + \dot{Ex}_{15}}{\dot{Ex}_8 + \dot{Ex}_{16}} \times 100$
11	Plate heat exchanger (Water 18 in, Steam 25 in, Condensate 26 out, Hot water 15 out)	$\dot{m}_{18} + \dot{m}_{25} = \dot{m}_{26} + \dot{m}_{15}$ $\dot{E}_L = (\dot{E}_{18} + \dot{E}_{25}) - (\dot{E}_{26} + \dot{E}_{15})$ $\dot{Ex}_D = (\dot{Ex}_{18} + \dot{Ex}_{25}) - (\dot{Ex}_{26} + \dot{Ex}_{15})$ $\eta = \frac{\dot{E}_{18} + \dot{E}_{25}}{\dot{E}_{15} + \dot{E}_{26}} \times 100$ $\psi = \frac{\dot{Ex}_{18} + \dot{Ex}_{25}}{\dot{Ex}_{15} + \dot{Ex}_{26}} \times 100$
12	Plate heat exchanger (Chilled water 20 in, Pasteurised cream 10 in, Pasteurised cream 11 out, Cold water 21 out)	$\dot{m}_{10} + \dot{m}_{20} = \dot{m}_{11} + \dot{m}_{21}$ $\dot{E}_L = (\dot{E}_{10} + \dot{E}_{20}) - (\dot{E}_{11} + \dot{E}_{21})$ $\dot{Ex}_D = (\dot{Ex}_{10} + \dot{Ex}_{20}) - (\dot{Ex}_{11} + \dot{Ex}_{21})$ $\eta = \frac{\dot{E}_{10} + \dot{E}_{20}}{\dot{E}_{11} + \dot{E}_{21}} \times 100$ $\psi = \frac{\dot{Ex}_{10} + \dot{Ex}_{20}}{\dot{Ex}_{11} + \dot{Ex}_{21}} \times 100$
13	Condenser & fan combination (Air in 22, Electricity 33, Makeup water 24, Water 12 in, Water 13 out, Air out 23)	$\dot{m}_{12} + \dot{m}_{22} + \dot{m}_{24} = \dot{m}_{13} + \dot{m}_{23}$ $\dot{E}_L = (\dot{E}_{12} + \dot{E}_{22} + \dot{W}_{33} + \dot{E}_{24}) - (\dot{E}_{13} + \dot{E}_{23})$ $\dot{Ex}_D = (\dot{E}_{12} + \dot{Ex}_{22} + \dot{W}_{33} + \dot{E}_{24}) - (\dot{Ex}_{13} + \dot{Ex}_{23})$ $\eta = \frac{\dot{E}_{13} + \dot{E}_{23}}{\dot{E}_{12} + \dot{E}_{22} + \dot{E}_{24} + W_{33}} \times 100$ $\psi = \frac{\dot{Ex}_{13} + \dot{Ex}_{23}}{\dot{Ex}_{12} + \dot{Ex}_{22} + \dot{Ex}_{24} + W_{33}} \times 100$

Table 3 (continued)

S. no.	Component	Energy and exergy relations
14	Fresh water 19 16 → Water tank → 17 Water Water	$\dot{m}_{16} + \dot{m}_{19} = \dot{m}_{17}$ $\dot{E}_L = (\dot{E}_{16} + \dot{E}_{19}) - (\dot{E}_{17})$ $\dot{Ex}_D = (\dot{Ex}_{16} + \dot{Ex}_{19}) - (\dot{Ex}_{17})$ $\eta = \frac{\dot{E}_{17}}{\dot{E}_{16} + \dot{E}_{19}} \times 100$ $\psi = \frac{\dot{Ex}_{17}}{\dot{Ex}_{16} + \dot{Ex}_{19}} \times 100$

estimation of cost flow rates for each of the subunits at all input and output points, thereby covering entire of the plant, to secure optimum cost matrix in relation to exergetic destruction [23, 24].

As per the said methodology, cost accounting for each of the units of exergy approaching and leaving the subunit is quantified in terms of cost which is called as fuel input and product output in general. Moreover, mathematically, cost balance expressions are evolved in coordination with exergy flow streams for all subunits of plant. The relations of exergy transmission and cost flow rates per unit exergy for thermal and electrical energy contents may be written as:

$$\dot{C}_i = c_i \dot{Ex}_i \tag{7}$$

$$\dot{C}_e = c_e \dot{Ex}_e \tag{8}$$

$$\dot{C}_w = c_w \dot{Ex}_w \tag{9}$$

$$\dot{C}_q = c_q \dot{Ex}_q \tag{10}$$

Further, overall exergoeconomic equilibrium equation for all the subunits of plant may be given as follows:

$$\sum_i \left(c_i \dot{Ex}_i \right) + c_w \dot{Ex}_w + \dot{Z}_k = \sum_e \left(c_e \dot{Ex}_e \right) + c_q \dot{Ex}_q \tag{11}$$

The above stated equation is the reflection of the fact that summation of cost rates of approaching exergy streams equals to sum total of cost rates of all leaving exergy streams in addition to capital and other related costs. Additionally, in exergy cost balance equation, all the terms present in the aforementioned equation are positive in nature. Moreover, SPECO methodology of exergoeconomic analysis entails that there exists $n - 1$ number of auxiliary set of equations for n number of exergy leaving streams involving cost flow rates which highlight the significance of F and P propositions of SPECO methodology [23, 24].

The F and P approaches impart price value to incoming and outgoing exergy streams along with establishment of cost equilibrium of exergy streams for fuel and product side. In the present section, auxiliary equations as constraints are mapped against corresponding cost flow rates of

existing exergy streams for each of the constituents of cream pasteurisation plant. In an extension to same approach, capital investment as well as operational and maintenance costs are expressed as hourly levelised cost rate for flow streams at each entry and exit point of the plant. Therefore, the summation of above-mentioned levelised cost rates can be represented as follows:

$$\dot{Z}_T = \dot{Z}_{CI} + \dot{Z}_{OM} \tag{12}$$

The algorithm as specified in next six steps was instituted for computation of hourly levelised cost rate for each subunit of plant. For cream pasteurisation plant, the parameter present worth (PW) was determined by the following relationship as:

$$PW = TCI - S \times PWF \tag{13}$$

where TCI and S stand for total capital investment at initial stage and salvage value of plant at any stage of plant operation. The former was identified as Rs. 550,000, while the latter was calculated from the relationship as mentioned below.

$$S = TCI \times J \tag{14}$$

Additionally, the ratio of salvage value was denoted by term J, which was taken as 8% for the purpose of current analysis. Similarly, single payment present worth factor (PWF) can be mathematically expressed as:

$$PWF = \frac{1}{(1+i)^n} \tag{15}$$

wherein i stands for annual interest rate value, i.e. 10%, and n indicates number of years, i.e. 10, for which the pasteurisation unit was operational. By multiplication of numerical value of present worth and capital recovery factors, annual cost of entire plant could be secured as given by the following equation.

$$AC = PW \times CRF \tag{16}$$

The capital recovery factor (CRF), as discussed above, can be computed by the following mathematical relationship as:

Table 4 Key derivatives related to exergoeconomic evaluation of subunits of cream pasteurisation plant [24]

S. no.	Name of the derivative	Mathematical relationship
1	Percentage relative cost difference	$r_k = \frac{\dot{c}_{f,k} - \dot{c}_{p,k}}{\dot{c}_{f,k}} \times 100$
2	Cost rate of exergetic degradation	$\dot{D}_{D,k} = \dot{Ex}_{D,k} \times c_{f,k}$
3	Exergoeconomic factor	$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k} \times \dot{Ex}_{D,k}} \times 100$

$$CWF = \frac{i(i+1)^n}{(1+i)^n - 1} \quad (17)$$

The cream pasteurisation activity was performed continuous for 300 days in a year and 7 h on daily basis. The operational and maintenance cost dedicated for the 2100 h of annual operation of plant was estimated as Rs. 183,150. Finally, annualised cost of equipment for the plant was given by the following mathematical equation.

$$Z_{T,k} = \left[(1 + \phi) \frac{AC}{\tau} \right] \times \frac{PEC}{\sum PEC} \quad (18)$$

where τ, AC and PEC are total number of hours for which the plant is operational in a year, annual cost of subunit and cost of each subunit of plant, respectively. Thus, aforementioned algorithm assists in procurement of hourly levelised cost of capital investment $Z_{CI,k}$(Rs. H^{-1}), operational and maintenance cost $Z_{OM,k}$(Rs. H^{-1}) as 52.52 (Rs. H^{-1}) and 17.33 (Rs. H^{-1}), respectively. In addition to that, overall levelised cost rate, i.e. $Z_{T,k}$(Rs. H^{-1}), of plant is the summation of above-mentioned two levelised cost rates, i.e. 69.86 (Rs. H^{-1}).

Exergoeconomic parameters

This section enumerates some of the main parameters related to exergoeconomic analysis, i.e. average value of cost per unit exergy for the fuel and product for any subunit k of plant, and the same are represented by the following mathematical equations as:

$$c_{f,k} = \frac{\dot{C}_{f,k}}{\dot{Ex}_{f,k}} \quad (19)$$

$$c_{p,k} = \frac{\dot{C}_{p,k}}{\dot{Ex}_{p,k}} \quad (20)$$

where $\dot{C}_{f,k}$ and $\dot{C}_{p,k}$ are the total cost flow rates for each of the subunits in fuel as well as product side, on the basis of which key exergoeconomic indices such as cost rate of exergetic degradation ($\dot{D}_{D,k}$), exergoeconomic factor (f_k) and relative cost difference in terms of percentage value(r_k) were ascertained by developing relationships as given in Table 4.

Basically, parameters mentioned in Table 4 collectively help in providing ranks to subunits of plant as per their order of exergoeconomic performance or characteristics. The magnitude of irreversibility or thermodynamic incompetency is quantified in terms of cost rate of exergetic degradation for any subunit of plant. Besides that, exergoeconomic factor in combination with percentage relative cost difference helps in diagnosis of level of penetration of capital investment or involvement of cost rate of exergetic degradation in overall cost composition matrix of cream pasteurisation plant; in other words, validation of exergoeconomic performance of plant could be fruitfully secured by logical outcomes of aforementioned indices.

Apart from the above discussion, percentage relative cost difference values (r_k) for each of the plant constituents reflect amount of increment or decrement in cost rate of exergetic destruction received or experienced by subunit under consideration, while processing material through it. Moreover, it is established as a better index of measurement of exergoeconomic performance, i.e. with the help of which, relative estimation of performances of subunits is ascertained in relation to total operating cost rate of plant. The idea of exergoeconomic approach is to develop or strike an optimum balance between amount of capital investment to be made in a certain venture and degree of thermodynamic perfection to be procured out of it. The major goals of exergoeconomic appraisal were recognised as follows:

- To examine the exact location and definite magnitude of exergy destruction and cost thereof in an energy system.
- To estimate precisely the specific manufacturing cost (Rs. kg^{-1}) of final product.
- To evolve technical policies and programmes with a view of upgrading thermal performance of processing plant.
- To pinpoint or discover different approaches for achievement of maximum performance in line with reduction in overall operational cost of plant.
- To determine the trade-off amongst techno-economic variables so as to assess suitability of different options for plant activities.

The exergetic cost rate equilibrium equations for each subunit of cream pasteurisation plant are given in Table 5.

In addition to aforementioned mathematical formulation of thermodynamics and thermoeconomic appraisals, the specific heat capacity and specific volume of milk constituents could be represented as a function of the state temperature as displayed in Table 6.

Additionally, subsequent equations were instituted for computation of specific volume and specific heat capacities

Table 5 Exergetic cost rate equilibrium equations for subunits of cream pasteurisation plant [24]

S. no.	Component	Exergetic cost rate balance equations for main Units of HTST cream pasteurisation plant	Auxiliary equations
1	Storage tank	$\dot{C}_1 + \dot{C}_{27} + \dot{Z}_{T,ST} = \dot{C}_2$	$c_5 = c_8 = c_9$
2	Pump-1	$\dot{C}_2 + \dot{C}_{28} + \dot{Z}_{T,P1} = \dot{C}_3$	$c_{12} = c_{15} = c_{16}$
3	Balance tank	$\dot{C}_3 + \dot{Z}_{T,BT} = \dot{C}_4$	$c_{20} = c_{21}$
4	Pump-2	$\dot{C}_4 + \dot{C}_{29} + \dot{Z}_{T,P2} = \dot{C}_5$	$c_{24} = c_{19} = 0$
5	Pump-3	$\dot{C}_6 + \dot{C}_{30} + \dot{Z}_{T,P3} = \dot{C}_7$	$c_{22} = c_{23} = 0$
6	Pump-4	$\dot{C}_{13} + \dot{C}_{32} + \dot{Z}_{T,P4} = \dot{C}_{14}$	
7	Pump-5	$\dot{C}_{17} + \dot{C}_{31} + \dot{Z}_{T,P5} = \dot{C}_{18}$	
8	Cooling section	$\dot{C}_9 + \dot{C}_{14} + \dot{Z}_{T,CS} = \dot{C}_{12}$	
9	Regeneration section	$\dot{C}_5 + \dot{C}_8 + \dot{Z}_{T,RS} = \dot{C}_6 + \dot{C}_9$	
10	Heating section	$\dot{C}_7 + \dot{C}_{15} + \dot{Z}_{T,HS} = \dot{C}_8 + \dot{C}_{16}$	
11	Heat exchanger	$\dot{C}_{25} + \dot{C}_{18} + \dot{Z}_{T,HE} = \dot{C}_{15} + \dot{C}_{26}$	
12	Chilling section	$\dot{C}_{10} + \dot{C}_{20} + \dot{Z}_{T,CHS} = \dot{C}_{11} + \dot{C}_{21}$	
13	Condenser and fan combination	$\dot{C}_{12} + \dot{C}_{22} + \dot{C}_{33} + \dot{C}_{24} + \dot{Z}_{T,CF} = \dot{C}_{23} + \dot{C}_{32}$	
14	Water tank	$\dot{C}_{16} + \dot{C}_{19} + \dot{Z}_{T,WT} = \dot{C}_{17}$	

Table 6 Relation for density and specific heat capacity of milk derivatives [40]

Component	Density relation	Specific heat capacity relation
Protein	$\rho_{protein} = 2.0082 \times 10^3 - \frac{5.184 \times T}{10}$	$c_{p,protein} = 2.0082 + \frac{1.2089 \times T}{10^3} - \frac{1.3129 \times T^2}{10^6}$
Fat	$\rho_{fat} = 9.2559 \times 10^2 - \frac{4.1757 \times T}{10}$	$c_{p,fat} = 21.9842 + \frac{1.4733 \times T}{10^3} - \frac{4.808 \times T^2}{10^6}$
Carbohydrate	$\rho_{carbohydrate} = 1.5991 \times 10^3 - \frac{3.1046 \times T}{10}$	$c_{p,carbohydrate} = 1.5488 + \frac{1.9625 \times T}{10^3} - \frac{5.9399 \times T^2}{10^6}$
Ash	$\rho_{ash} = 2.4238 \times 10^3 - \frac{2.8063 \times T}{10}$	$c_{p,ash} = 1.0926 + \frac{1.8896 \times T}{10^3} - \frac{3.6817 \times T^2}{10^6}$
Water	$\rho_{water} = 9.9718 \times 10^3 + \frac{3.1439 \times T}{10^3} - \frac{3.7574 \times T^2}{10^3}$	$c_{p,water} = 4.1762 + \frac{9.0864 \times T}{10^3} - \frac{5.4731 \times T^2}{10^6}$

Table 7 Composition of milk derivatives for variable fat contents [40]

Constituents	Water	Fat	Carbohydrate	Protein	Ash
Fraction in 3.6% fat milk	0.8780	0.0360	0.0458	0.0324	0.0078
Fraction in 0.05% fat milk	0.9103	0.0005	0.0475	0.0336	0.0081
Fraction in 40% fat milk	0.5465	0.4000	0.0285	0.0202	0.0048
Fraction in 12% fat milk	0.8015	0.1200	0.0418	0.0296	0.0071

of milk derivatives at all state positions of plant, respectively.

$$c_p = \sum_i Y_i \times c_{p,i} \qquad (21)$$

$$v = \sum_i \frac{X_i}{\rho_i} \qquad (22)$$

Further, the composition of milk with variable fat content employed for calculation of specific volume and heat capacity is displayed in Table 7.

Table 8 Values of exergy and energy at all state points of cream processing plant

S. no.	State	T/K	P/bar	$\dot{m}$/kg s^{-1}	Exergy/kW	Energy/kW
1	40% F	327.15	1	0.672	0.98	2.97
2	40% F	327.15	1	0.672	0.98	2.97
3	40% F	327.15	2	0.672	2.00	3.04
4	40% F	327.15	1.5	0.672	1.48	3.01
5	40% F	327.15	3	0.672	3.07	3.12
6	40% F	351.27	2.35	0.672	7.40	9.60
7	40% F	351.27	4.5	0.672	14.40	9.76
8	40% F	363.15	4.25	0.672	19.73	14.15
9	40% F	335.15	4	0.672	6.53	4.98
10	40% F	308.65	3.5	0.672	0.67	0.58
11	40% F	280.15	3.25	0.672	7.10	1.43
12	HW	305.15	2.5	2.016	− 2.50	0.99
13	NW	300.15	1	2.016	− 0.06	0.06
14	NW	300.15	3	2.016	− 1.40	0.46
15	HW	372.15	1.5	0.2	7.95	6.62
16	NW	329.27	1.25	0.2	1.28	1.28
17	water	328.77	1.15	0.2	1.14	1.24
18	Water	328.77	3.5	0.2	3.59	1.28
19	Water	298.15	2	0.00025	0.00	0.00
20	Chilled water	274.15	2.5	2.016	202.49	8.92
21	Cold water	281.65	2	2.016	160.30	4.20
22	Air (RH = 24%)	298.15	1	0.01	0.00	0.00
23	Air (RH = 100%)	300.15	1	0.01	0.00	0.00
24	Water	298.15	2	0.00007	0.00	0.00
25	Steam	400.56	3.5	0.02	52.54	13.35
26	Condensate	400.15	2.83	0.02	10.49	1.38
34	Chilled water	274.15	2.5	2.016	202.49	8.92
35	Cold water	281.65	2	2.016	160.30	4.20

Uncertainty analysis

In order to ascertain the replication and characterisation of exploratory figures, the necessary course of action related to uncertainty analysis was effectuated with the help of approach developed by Holman [41].

$$U = \left[\left\rangle \frac{\partial F}{\partial z_1} u_1 + \frac{\partial F}{\partial z_2} u_2 \cdots + \frac{\partial F}{\partial z_n} u_n \right] \tag{23}$$

Results and discussions

Thermodynamic analysis

The cream pasteurisation plant mainly consists of cream pasteuriser which involved regeneration, heating, cooling and chilling activities. All of the key thermodynamic variables such as working pressure and temperature along with mass flow rates of milk flow streams at all state positions as depicted in Fig. 1 are listed out in Table 8, with the help of which, thermal performance parameters were figured out for each of the constituents of cream pasteurisation plant as shown in Tables 9 and 10.

The energy and exergy efficiency of cream pasteurisation plant was calculated to be 86.88% and 66.11%, respectively (Tables 9, 10), for complete cream pasteurisation plant. However, from the earlier research attempts [9, 27, 40], the variation in exergetic performances for milk pasteurisation line was reported to be in the range of 78.00–92.02% while energy efficiency was registered in between 68 and 72% [42]. Amongst the key processing subunits of the plant, the highest value of exergy efficiency was reported for heating section (94.14%) followed by regeneration section (84.42%) and final chilling section (59.26%) (Fig. 2). However, their corresponding energy counterparts were calculated as 94.91%, 95.88% and 74.05%, respectively. The least value of energy and exergy efficiencies was recognised for cooling tower, i.e. 27.86%

Table 9 Derivatives of energy analysis for all components of cream processing plant

S. no.	Item	E_{in}/kW	E_{out}/kW	E_L/kW	η/%	E_{IP}/kW	$E_{\beta, k}$	$E_{F,k}$
1	Storage Tank	268.68	225.89	42.79	84.07	6.81	21.43	17.66
2	Pump-1	66.59	65.09	1.5	97.75	0.03	0.75	4.38
3	Balance tank	65.09	65.09	0	100.00	0.00	0.00	4.28
4	Pump-2	67.29	65.09	2.2	96.73	0.07	1.10	4.42
5	Regeneration section	210.98	202.28	8.7	95.88	0.36	4.36	13.86
6	Pump-3	124.23	119.23	5.00	95.98	0.20	2.50	8.16
7	Heating section	181.17	171.94	9.23	94.91	0.47	4.62	11.91
8	Cooling section	99.92	82.63	17.29	82.70	2.99	8.66	6.57
9	Chilling section	226.06	167.4	58.66	74.05	15.22	29.38	14.86
10	Heat exchanger	78.17	72.43	5.74	92.66	0.42	2.87	5.14
11	Pump-5	27.88	25.63	2.25	91.93	0.18	1.13	1.83
12	Water tank	26.05	25.63	0.42	98.39	0.01	0.21	1.71
13	Pump-4	19.07	16.87	2.2	88.46	0.25	1.10	1.25
14	Condenser and fan combination	60.56	16.87	43.69	27.86	31.52	21.88	3.98

Table 10 Derivatives of exergy analysis for all components of cream processing plant

S. no.	Item	Ex_{in}/kW	Ex_{out}/kW	Ex_D/kW	ψ/%	Ex_{IP}/kW	$Ex_{\beta,k}$	$Ex_{F,k}$	SI_k
1	Storage tank	12.39	7.17	5.22	57.87	2.20	13.70	11.02	2.37
2	Pump-1	4.47	3.04	1.43	4.67	1.36	3.75	3.98	1.05
3	Balance tank	3.04	3.01	0.03	99.01	0.00	0.08	2.70	0.00
4	Pump-2	5.21	3.12	2.09	5.00	1.99	5.48	4.63	1.05
5	Regeneration section	17.27	14.58	2.69	84.42	0.42	7.06	15.36	6.42
6	Pump-3	14.6	9.76	4.84	3.20	4.69	12.70	12.98	1.03
7	Heating section	16.38	15.42	0.96	94.14	0.06	2.52	14.57	17.06
8	Cooling section	5.44	1.57	3.87	28.86	2.75	10.15	4.84	1.41
9	Final chilling	9.5	5.63	3.87	59.26	1.58	10.15	8.45	2.45
10	Heat exchanger	14.63	8	6.63	54.68	3.00	17.40	13.01	2.21
11	Pump-5	3.49	1.28	2.21	1.78	2.17	5.80	3.10	1.02
12	Water tank	1.28	1.24	0.04	96.88	0.00	0.10	1.14	32.00
13	Pump-4	2.26	0.46	1.8	18.18	1.47	4.72	2.01	1.22
14	Condenser and fan combination	2.49	0.06	2.43	2.41	2.37	6.38	2.21	1.02

and 2.41%, respectively, owing to higher level of energy loss through the unit.

The energy and exergy efficiencies of centrifugal pumps were estimated to be in the range of 88.46–97.75% and 1.78–18.18%, respectively. The second law efficiency of subunit cream pasteuriser possessed the numerical figure as 76.56%, while the variation in same in previous research approaches [9, 27, 40] was gauged to be in the range of 72.42–88.56%. Similarly, the exergy efficiency of cream storage tank and water storage tank was ascertained to be 57.87% and 96.88%, respectively. Further, exergy efficiency of four subsections, e.g. regeneration section, heating section, cooling section and chilling section, of

cream pasteurisation unit was determined as 84.42%, 94.14%, 28.86% and 59.26%, respectively.

Similarly, previously recorded [9, 27, 40] variation in exergy efficiency for plate heat exchanger required for hot water generation unit was reported to be in the range of 50.53–53.32% as against 54.68%, determined in current research endeavour. Moreover, value of specific steam consumption for cream pasteurisation line was estimated to be 0.03 kg kg^{-1}, which lies in the range of 0.02–0.05 kg kg^{-1} as discussed in the aforementioned literature reviews. The total value of specific energy loss for the entire plant was registered as 297.12 kJ kg^{-1}, while exergy counterpart of the same recorded a magnitude of
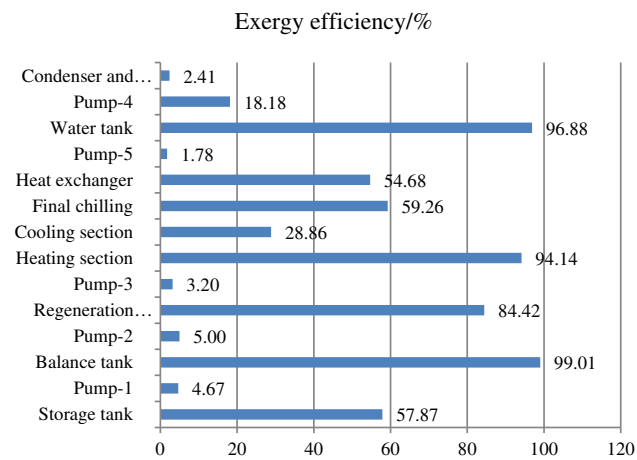
Exergy efficiency/%

Fig. 2 Exergy efficiency for each subunit of HTST cream pasteurisation plant
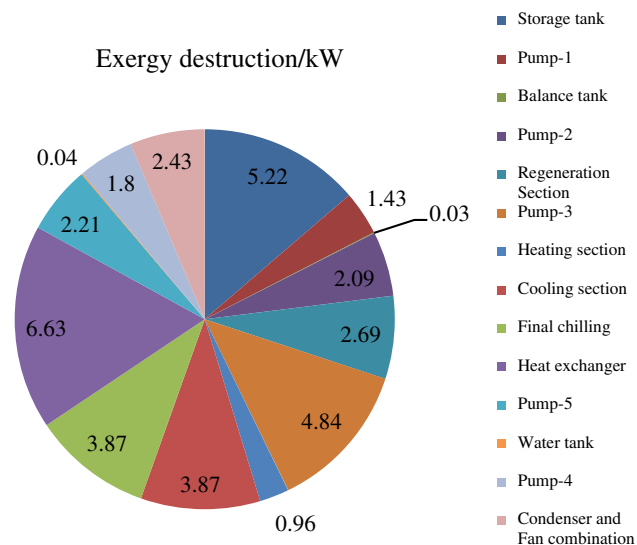
Exergy destruction/kW

Fig. 3 Exergy destruction for each subunit of HTST cream pasteurisation plant

56.71 kJ kg^{-1} (Tables 9, 10). In an extension to the same, some of the recent research ventures also identified specific degradation in exergy of milk processing units in the ambit of 25.67–77.62 kJ kg^{-1}, wherein constituents involved in regeneration exercises maintained almost similar numerical magnitude for second law efficiency (84.42%) as specifically mentioned in previous research documentation related to milk processing or pasteurisation, i.e. 82.00–89.84% [9, 27, 40].

The total value of energy loss for the complete cream pasteuriser was enumerated to be 93.88 kW whereas its corresponding exergetic counterpart was determined as 11.39 kW (Fig. 3). The subscription of heating and cooling activities towards total exergy destruction was diagnosed as 19.91% and 40.38%, respectively. The share of pumping

Exergy improvement potential (kW)

Fig. 4 Exergy improvement potential for each subunit of HTST cream pasteurisation plant

and storage activities towards the overall exergy demolition was reported as 46.34%, and its energy counterpart was calculated as 28.22%. It is quite important to note that electrical energy requirements of the pumping systems in dairy processing plants can be significantly reduced by employing variable speed drive (VSD) controller.

Heat exchanger, being the key constituent of the plant, was associated with gross exergy destruction of 6.63 kW, followed by final chilling or intermediate cooling; the numeric quantification of the same was expressed as 3.87 kW. A little glance over the energy and exergy derivatives of plant indicated that value of energy loss and exergy destruction for the condenser and fan combination was confirmed as 43.69 kW and 2.41 kW, respectively. Amongst the key processing units of the plant, the highest value of exergy destruction was reported for heat exchanger (6.63 kW), followed by exergetic degradation in cream storage tank (5.22 kW) and cooling or final chilling section (3.87 kW) (Fig. 3).

The demolition of cool exergy content [11] in the cream storage tank was primarily caused by higher degree of cooling, mainly needed for accomplishment of instantaneous crystallisation of milk fat or effective cream ripening, so that highest possible butter yield could be obtained. The structural strength or mechanical integrity of milk fat is essentially achieved by carrying out milk/cream chilling at higher rates in association with by non-violent agitation of milk fat in cream storage tank. The development of high grade partial coalescence amongst milk fat globules or inception of Van der Waal's forces of attraction between the liquid and solid phases of milk fat is achieved at the cost of sufficient amount of cool exergy demolition, i.e. 7.77 kJ kg^{-1} of pasteurised cream.

Specific exergy consumption/%

- Electrical energy
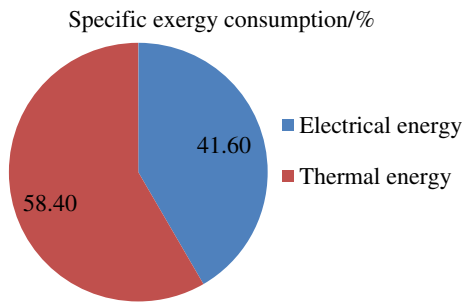- Thermal energy

41.60
58.40

Fig. 5 Percentile subscription of exergy to the specific exergy consumption in cream processing plant

In addition to accomplishment of complete bacteriological control over milk cream through pasteurisation, it is quite important to note that in order to secure highest possible texture quality as well as butter yield, it is highly imperative to maintain final temperature of outgoing pasteurised cream in the range of 8–12 °C, as the said temperature range also assists in control of fat loss during the churning process for butter production [43].

The specific energy improvement potential of the entire cream pasteurisation plant was computed to be 87.12 kJ kg^{-1}, while its exergetic counterpart registered a magnitude of 35.80 kJ kg^{-1} (Tables 9, 10). The energy and exergy improvement potential related to cream pasteuriser was enumerated to be 19.04 kW and 4.81 kW, respectively. The maximum value of exergy improvement potential is registered in case of water tank (4.69 kW) followed by that of heat exchanger (3.00 kW), cooling section (2.75 kW) and condenser and fan combination (2.37 kW) (Fig. 4).

The cumulative value of exergy improvement potential for pumping operation in plant was calculated as 11.68 kW, while contribution rendered by cream storage units was 9.14% towards the same. The scope of exergy improvement potential for condenser and fan combination was diagnosed to be 2.37 kW. However, heat exchanger being one of the key thermodynamic entities of the pasteurisation plant scored maximum magnitude of relative exergy destruction ratio, i.e. 17.40% followed by cooling or chilling section (10.15%) and regeneration section (7.06%), respectively (Table 10). The higher rates of degradation of high grade energy potential in plate heat exchangers could be attributed to heat transfer with comparatively greater magnitudes of thermal gradients in hot and cold side.

Besides that, the exergetic deficiency of the cream pasteuriser was valued to be 23.44%, displaying its satisfactory performance characteristics in retrieving the 'warm' and 'cool' exergies of flow streams involved in regeneration or heat transfer activity [27]. However, the exergetic performances of HTST cream pasteurisation plant can be markedly improved by involving innovative perspectives such as self-heat recuperation mechanism wherein both latent heat and sensible heat of the streams can be reclaimed into a process based upon recuperation of exergy content, causing significant amount of resource saving in the activity just mentioned. Moreover, the combined exergy and pinch tools can be effectively instituted for retrofitting and designing of food pasteurisation plants [44].

Table 11 Values of exergoeconomic indices for constituents of the cream processing plant

| S. no.	Item	PEC (Rs.)	$\dot{Z}_{CI,k}$/Rs. H^{-1}	$\dot{Z}_{OM,k}$/Rs. H^{-1}	$\dot{Z}_{T,k}$/Rs. H^{-1}	$\dot{D}_{D,k}$/Rs. H^{-1}	r_k/%	f_k/%	TOCR$_k$/Rs. H^{-1}
1	Storage tank	41,000	3.92	1.29	5.21	42.26	23.99	4.68	47.47
2	Pump-1	22,000	2.10	0.69	2.79	15.28	22.66	15.46	18.08
3	Balance tank	10,000	0.96	0.32	1.27	0.41	4.05	75.39	1.68
4	Pump-2	22,000	2.10	0.69	2.79	30.10	40.79	8.49	32.90
5	Regeneration section	112,000	10.70	3.53	14.23	130.76	10.92	9.81	144.99
6	Pump-3	22,000	2.10	0.69	2.79	146.47	1.88	1.87	149.26
7	Heating section	41,000	3.92	1.29	5.21	30.09	17.22	14.75	35.30
8	Cooling section	100,000	9.55	3.15	12.70	344.84	67.79	3.55	357.55
9	Chilling section	40,000	3.82	1.26	5.08	612.49	43.83	0.82	617.57
10	Heat Exchanger	45,000	4.30	1.42	5.72	73.99	38.00	7.17	79.71
11	Pump-5	22,000	2.10	0.69	2.79	18.38	48.21	13.20	21.17
12	Water tank	10,000	0.96	0.32	1.27	0.28	15.15	81.82	1.55
13	Pump-4	22,000	2.10	0.69	2.79	116.64	73.14	2.34	119.43
14	Condenser and fan combination	41,000	3.92	1.29	5.21	17.23	97.97	23.20	22.44

Total operating cost rate/Rs. H^{-1})
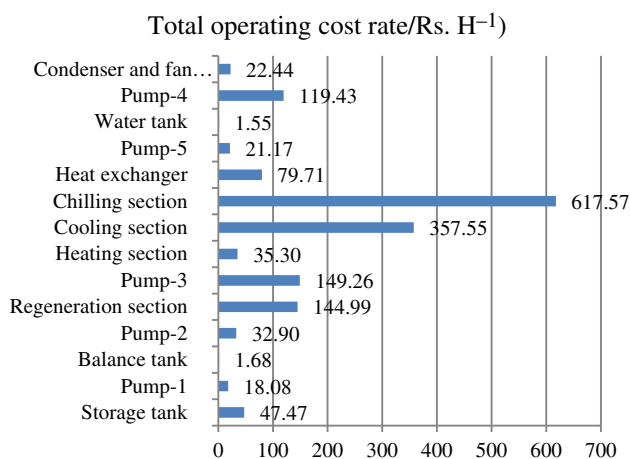
Fig. 6 Comprehensive operational costs for subunits of cream processing plant

The detailed investigation of Table 10 revealed that the share of cream pasteuriser towards total exergy degradation was unlocked to be 29.89% against an exergetic factor of 43.21%. The highest value of the exergetic factor was recorded for regeneration section (15.36%) followed by heating section (14.57%) and heat exchanger (13.01%).

The highest value of sustainability index was realised for heating section (SI: 17.06) followed by regeneration section (SI: 6.42) and chilling section (SI: 2.45); however, the same parameter registered a value of 4.27 for cream pasteuriser. The sustainability index for the heat exchanger was estimated to be one-third and nearly two times to that of regeneration and cooling section, respectively. In comparison with chilling section as discussed above, the heating section was expressed 2.85 times better sustainability characteristics.

As far as specific thermal and electrical exergy consumption is concerned, the literature has provided the variation in same in the range of 18.00–35.98 kJ kg^{-1} and 8.82–18.17 kJ kg^{-1}, respectively [9, 27, 40], whereas the present study has reported the magnitude of aforementioned parameters as 31.86 kJ kg^{-1} and 22.69 kJ kg^{-1}, respectively.

Thus, from Table 10, it could be suitably concluded that the subunit cream pasteuriser sustained good thermodynamic ranking and, in comparison with the earlier literatures [9, 27, 40], better sustainable characteristics were reflected by plate heat exchanger required for hot water generation. Moreover, 58.40% share of resources consumption had been fulfilled by thermal energy while remaining portion of exergy consumption was furnished by the electrical energy counterpart (Fig. 5).
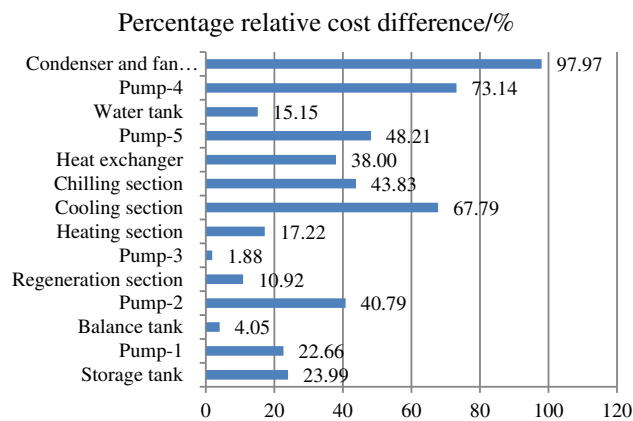
Percentage relative cost difference/%

Fig. 7 Value of percentage relative cost difference of each ingredient of cream processing plant

Thermoeconomic analysis

In the current section, the exergoeconomic statuses of individual constituent as well as those of cream pasteuriser have been established. The indices of thermodynamic assessment have been quantified, and their physical significance in relation to each other was explored. The SPECO technique of exergoeconomic analysis was employed to capture the bottom line of its derivatives and predict the scope of improvement within the current architecture of the plant.

The outcomes of thermoeconomic assessments were synopsised in Table 11, which demonstrated the calibration of principal exergoeconomic indices such as cost of exergy destruction, percentage relative cost difference, levelised cost rate of components, exergoeconomic factor and comprehensive operational cost of overall plant and its constituents.

The exigency of overall operating cost rate could be described in terms of the fact that higher the dominance of comprehensive operational cost rate of entire plant, the higher will be the percussion of a constituent on the behaviour of the overall performance system. The cumulative hourly levelised cost rate of the entire plant was estimated to be 69.86 Rs. H^{-1}, maximum contribution to which was made by cream pasteuriser (53.28%) followed by pumping and storage units (31.60%) while the rest of the contribution was made by heat exchanger and condenser and fan combination, i.e. 15.65%.

From Table 11, the percentage relative cost difference and exergoeconomic factor for the cream pasteurisation unit was calculated as 49.71% and 3.47%, respectively, which clearly indicated the majority share of total operating cost rate went into overcoming the thermal deficiencies present in the cream pasteurisation unit. The total operating cost rate for complete cream pasteurisation plant was
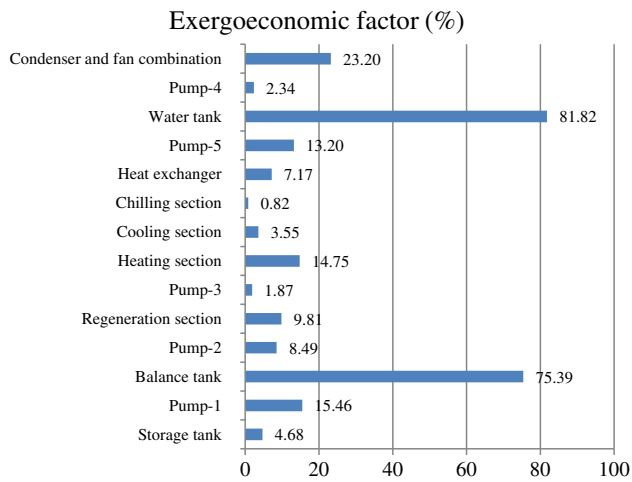
Exergoeconomic factor (%)

Fig. 8 exergoeconomic Factor for each of the constituents of HTST cream pasteurisation plant

Table 12 Uncertainty values in measurement of technical variables of cream processing plant

S. no.	Parameter	Total uncertainty
1	Cream temperature	± 1.2839
2	Cream pressure	± 0.30276
3	Cream mass flow rate	± 0.13704
4	Steam mass flow rate	± 0.00804
5	Steam pressure	± 0.34785

notified to be 1649.10 Rs. H^{-1}, 70.06% contribution to which was given by cream pasteuriser, respectively (Fig. 6). Amongst the subunits of cream pasteuriser such as regeneration section, heating section, cooling and chilling sections, cost rate of exergy destruction was enumerated to be highest for the chilling activity (617.57 Rs. H^{-1}) followed by cooling (357.55 Rs. H^{-1}) and regeneration activity (144.99 Rs. H^{-1}), respectively. The subscription of heating and cooling activities towards total operating cost rate was diagnosed to be 67.43%. Similarly, pumping and storage activities consumed 23.65% portion of total operating cost rate of entire plant.

A careful observation of exergoeconomic indices of electrical energy munching subunits of the plant divulged that exergy degradation was articulated more extrusive in case of cooling water supply pump and cream supply pump, as the same consumed 21.83% portion of total operating cost rate. The water and cream supply pumps may be replaced with variable speed drive controllers and screw pumps in order to improve overall efficiency of the plant.

Amongst the key thermodynamic entities of the plant, the highest and lowest value of total operating cost rate was

associated with chilling section and condenser and fan combination of the plant, i.e. 617.57 Rs. H^{-1} and 22.44 Rs. H^{-1}, respectively. The cost expenditure on entities associated with chilling and cooling activities was 14.31 times higher than its heating counterpart whereas the exergetic degradation of former was more than two times to that of latter. The magnitudes of percentage relative cost differences in cooling or chilling and heating activities of the plant reflected that the fluid chilling or cooling was far more costlier than its heating counterpart. Similarly, fluid pumping was found out to be costlier than fluid storage activity.

Apart from pumping and storage units of plant, the highest value of cream processing cost was related to condenser and fan combination (97.97%) owing to higher level of exergetic degradation, followed by cooling section (67.79%) and chilling section (43.83%) of pasteuriser. However, the magnitude of percentage relative cost difference for the subunits such as regeneration section (10.92%), heat exchanger (7.17%) and heating section (17.22%) reflected comparatively low value of fluid processing cost in relation to above discussed subunits (Fig. 7). From Table 11, it was quite obvious that pumping and storage activities of plant consumed sufficient amount of cost in overcoming the irreversibilities associated with processing of cream fluid from one stage to another stage of plant.

As far as exergoeconomic factor was concerned, for the key thermodynamic entities of plant, the highest and lowest value of the exergoeconomic factor was determined for heating section (14.75%) and chilling section (0.82%), which quantified the role of capital investment and cost rate of exergy destruction (Fig. 8). The impact of exergetic degradation was quite prominent in subunits such as regeneration section; cooling section and heat exchanger as the same were obvious from the numeric quantification of aforementioned subunits, i.e. 9.81%, 7.17 and 3.55%, respectively.

As far as thermoeconomic performance of pumping units was concerned, it was found that except for the pump-3, the value of exergoeconomic factor for other all pumping units was significantly higher, which showed that operational and maintenance expenses were on higher side compared to the former wherein exergy destruction was observed to be far more influential. Similar sort of behaviour was projected by performance of cream storage tank, wherein low value of exergoeconomic factor was primarily caused by high rate of thermodynamic irreversibilities present in it.

Further, the cost per unit exergy and exergetic cost of pasteurised cream were determined as 203.08 Rs. H^{-1} and 39.51 Rs. MJ^{-1}, respectively. In view of above discussed sequences of thermodynamic and thermoeconomic

outcomes, the optimisation of key derivative of exergy analysis, i.e. specific exergy demolition, is perceived to be highly indispensible as far as significant reduction in specific manufacturing cost of HTST sterilised cream is concerned, which in the present scenario was estimated to be 0.682 Rs. H^{-1}.

In the view of current scenario of cream production and consumption in Indian Subcontinent for variety of value-added dairy products, the appropriate alterations, modifications and retrofitting in cream pasteurisation plant in combination with other production entities of dairy plant could help in procurement of higher production rates of dairy products at current level of fuel or resource requirements. Also, it is quite feasible to design and mature solar or biomass energy-assisted cream sterilisation plant, wherein temperature requirement of 100–160 °C could be easily obtained and the same would be a recognised as great breakthrough in achieving decrement in dependence upon consumption of natural resources. Overall, exergy and thermoeconomic basis of system evaluation provide an equivalent alternative to many other available methodologies in the literature in pinpointing possible exergy recovery features in dairy plant, on grounds of which exergy-related economic retrenchment up to an outstanding level could be realised. As an expansion to above stated approach, mechanism such as life cycle judgement, pinch analysis, exergy-assisted gainful optimisation and exergoenvironmental viewpoints could help in construction of feasible interpretation about operational- and maintenance-related economic expenditures as well as in estimation of impact of environmental degradation on convoluted thermal system.

Uncertainty analysis

Table 12 displays magnitude of uncertainty for the key technical variables of HTST Cream Processing Unit, the magnitude of which indicated that same were within acceptable limit, i.e. less than 5%. The uncertainty analysis is performed, firstly, to take into the consideration the variation in reading inherently present in the instrument or gauge; secondly, to display the reproducibility and representativeness of the experimental data; thirdly, from the view point of milk food biochemistry, since the variation in parameters beyond a certain range could affect the qualitative features such as yield, fat content, texture, taste and properties of product under consideration. For example, optimum temperature range of cream storage is 8–12 °C, to realise optimum butter yield as well as minimise fat loss during subsequent operation, i.e. churning. Therefore, in the current work, the variation in uncertainty in cream storage temperature (7 °C in present work) is in line with the above stated requirement, i.e. ± 1.2839.

Conclusions

The quantification of derivatives of thermodynamics is highly significant particularly when there is optimum utilisation of resource concerned or qualitative measurement of deviation from reversible behaviour is of prime importance, the exact information of which would entail better version of identification of exergy destruction and their corresponding location in an energy system. The thermal analysis generates refined picture of resource consumption in combination with all available constraints so that an approach could be developed whereby goal of optimum resource allocation as well as implementation of optimised operational parameters could be realised to fruitfully avail the corresponding monetary benefits. The said line of action remains incomplete as long as there is no involvement of economic analysis or precisely exergoeconomic analysis, wherein each unit of exergy destruction is enumerated in terms of cost.

Moreover, rational costing of thermoeconomic variable based on exergy concept assists in evolution of optimal plant architecture, i.e. specific manufacturing cost of product and cost rate of exergy demolition are ascertained in most judicious way.

Hence, collective idea of indices from both the analyses, i.e. exergy and exergoeconomic, develops resourceful picture about maximum attainable performance from entire plant. Therefore, a systematic and optimised protocol for achievement of minimum level of thermodynamic irreversibility was pertinent from the viewpoint of improvement in quantitative and qualitative indices of energy, exergy and exergoeconomic coupled with magnification in thermodynamic and thermoeconomic fertility of overall processing plant.

The overall energy and exergy efficiency of HTST Cream Pasteurisation Plant was adjudged to be 86.88% and 66.11%, respectively. The energy and exergy efficiencies of cream pasteuriser were computed to be 86.93% and 76.56%, respectively. The total value of specific energy loss for the entire plant was registered as 297.13 kJ kg^{-1}, while exergy counterpart of the same recorded a magnitude of 56.71 kJ kg^{-1}. Similarly, the specific energy improvement potential of the entire cream pasteurisation plant was computed to be 87.13 kJ kg^{-1}, while its exergetic counterpart registered a magnitude of 35.80 kJ kg^{-1}. The share of auxiliary units such as condenser and fan combination and heat exchanger towards total exergy destruction was enumerated to be 23.77%, respectively.

The total value of energetic destruction for the complete cream pasteuriser was enumerated to be 93.88 kW whereas its corresponding exergetic counterpart was determined as 11.39 kW. The subsections of cream pasteurisation units

such as heating section and chilling section recorded cumulative energy and exergy improvement potentials as 19.04 kW and 4.81 kW, respectively. The highest and lowest value of percentage relative cost difference was related to condenser and fan combination (97.97%) and hot water generation unit (7.17%), respectively. The gravity of total operating cost rate could be enumerated in terms of the fact that higher the value of total operating cost rate, the higher would be the impact of constituent of overall performance of the plant.

The total operating cost rate cream pasteurisation plant was computed to be 1649.10 Rs. H^{-1}. Amongst the key processing activities of the cream pasteurisation plant, the cost rate of exergy destruction for cooling and chilling was reported to be highest, i.e. 957.33 Rs. H^{-1} followed by regeneration (130.76 Rs. H^{-1}) and heating (30.09 Rs. H^{-1}). In the wake of thermodynamic and thermoeconomic analysis, it was quite essential to procure the balanced value of thermoeconomic factor indices for all constituents of the plant so that specific manufacturing cost of pasteurised cream could be optimised which was reported to be 0.682 Rs. kg^{-1} in the current analysis.

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