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High energy efficient system design for incubation process and cooling of yoghurt

Yoğurtun inkübasyonu ve soğutulması için yüksek enerji verimli sistem tasarımı

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High Energy Efficient System Design for Incubation Process and Cooling of Yoghurt

Highlights

- *Designing of an efficient energy system for yoghurt production process.*
- *Rational approach to yoghurt production for dairy industry.*
- *Two separate room design for incubation and cooling of yoghurt.*
- *Explanation of important yoghurt production criteria.*
- *Thermodynamic analysis of incubation-cooling system.*

Graphical Abstract

Important yoghurt production criteria were explained. Two separate rooms were designed using energy efficient model.

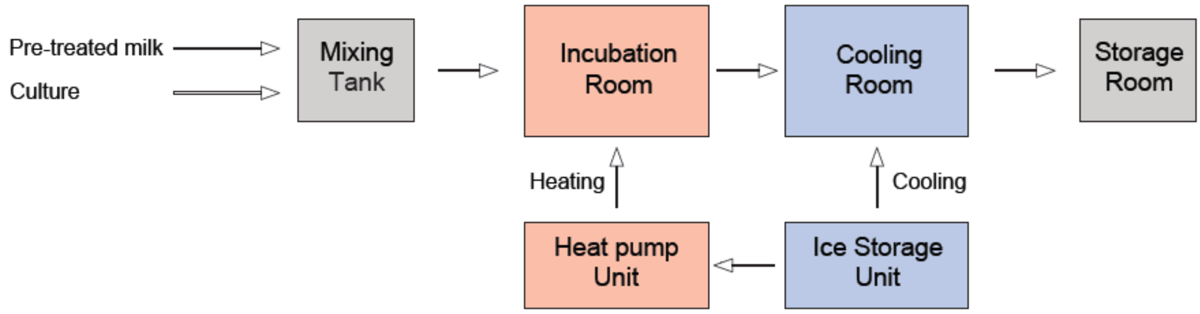

Figure. Design of the combined heating & cooling system

Aim

A system design for incubation process and cooling of yoghurt with two separate rooms was aimed to decrease the energy cost for the dairy industry.

Design & Methodology

A design has been made to produce yoghurt according to the standards by researching important criteria in yoghurt production.

Originality

A novel design was made using two separate rooms with high energy saving model.

Findings

With this study, energy is stored at a rate of 64/100 for R410a and a rate of 68/100 for R134a ($COP_{cooling}/COP_{heating}$) compared to the heat given independently of the incubation time.

Conclusion

An energy efficient-combined system which includes two separate rooms for yoghurt production has been designed. This study will provide important information to dairy producers.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Yoğurtun İnkübasyonu ve Soğutulması için Yüksek Enerji Verimli Sistem Tasarımı

Araştırma Makalesi / Research Article

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ÖZ

Gıda işleme çalışmaları, hem enerjinin verimli kullanımı hem de kaliteli ürünler elde etmek için önemlidir. Yoğurt, yaygın olarak tüketilen bir süt ürünüdür. Yoğurt üreten tesisler, geleneksel üretim yöntemlerinden dolayı yüksek enerji tüketmekte ve düşük verimlilikte çalışmaktadır. Kaliteli yoğurt üretmek için pastörize süt, maya türüne bağlı olarak 3-5 saat süreyle 42-45 °C'de tutulmalıdır, bu işlem inkübasyon olarak adlandırılır. İnkübasyon işleminden sonra, üretilen yoğurt, paket yoğurt büyüklüğüne bağlı olarak iki saat içerisinde 20 °C'ye kadar soğutulmalıdır. Geleneksel yoğurt üretim tesislerinde gerekli ısıtma ve soğutma birbirinden bağımsız olarak uygulanır ve bu yaklaşım yüksek enerji tüketimine, atık ısıya ve enerjinin verimsiz kullanılmasına neden olur. Bu çalışmada, daha yüksek enerji performansı ve verimliliği sağlamak için birbirinden bağımsız olarak aynı anda ısıtma ve/veya soğutma yapabilen ısı pompası ve ısı depolama ünitesinden oluşan kombine bir sistem tasarlanmıştır. Böylece, buharlaştırıcıdan ısı transferi için gerekli enerji ve inkübasyon sonrası soğutma depolanan buzdan sağlanmış ve ürünün ağırlığından bağımsız olarak her 100 birim ısıtma enerjisi için 64/68 birim enerji (soğutucu akışkana bağlı olarak) kazanılmıştır. Isıtma, soğutma ve ikili işletme seçenekleri için R410a ve R143a kullanan sistemin performans katsayısı (COP) sırasıyla 2.83, 1.83, 4.66 ve 3.16, 2.16, 5.31 olarak hesaplanmıştır. Isı pompası ve geleneksel doğalgaz-fuel-oil kazanları için enerji maliyetleri karşılaştırılmıştır. Sunulan tasarım ile yüksek enerji verimliliği ve düşük enerji tüketimi sağlanmış ve üretim tesislerinde kullanımı için öneriler verilmiştir.

Anahtar Kelimeler: Yoğurt inkübasyonu, enerji verimliliği, ısıtma, soğutma.

High Energy Efficient System Design for Incubation Process and Cooling of Yoghurt

ABSTRACT

Food processing studies are important for both efficient use of energy and to obtain quality products. Yoghurt is a dairy product which consumes widely. Yoghurt producing facilities consumes high energy and run at low efficiency due to their traditional production methods. In order to produce quality yoghurt, pasteurized milk should be kept at 42-45 oC for 3-5 hours depending on the yeast type, this process called as incubation. After the incubation process, produced yoghurt must be cooled down to 20 oC in two hours depending on the package size of yoghurt. In conventional yoghurt production facilities, required heating and cooling are applied independently and this approach causes high energy consumptions, waste heat and the inefficient use of energy. In this study, a combined system consisting of a heat pump and a heat storage unit which is capable of the simultaneously heating and/or cooling application independently of each other is designed to ensure higher energy performance and efficiency. Thus, the required energy for heat transfer from the evaporator and cooling after the incubation process was ensured from the stored ice and, independently of the weight of the product, 64/68 units of energy (depending of refrigerant) were gained for each 100 units of required heating energy.The coefficient of performance (COP) of the system using R410a and R134a for heating, cooling and dual operation modes were calculated as 2.83, 1.83, 4.66 and 3.16, 2.16, 5.31, respectively. Energy costs for heat pump and conventional natural gas-fuel-oil boilers were compared. High energy efficiency and low energy consumption have been provided with the presented design, and suggestions for use for production facilities are given.

Keywords: Incubation of yoghurt, energy efficiency, heating, cooling.

1. INTRODUCTION

Fermentation is one of the oldest methods used by human beings to extend the shelf life of food. Today, yoghurt is one of the most consumed fermented dairy products in the world. Yogurt passes through many stages which has high energy intensity until it is presented to the consumer. Since the human population is increasing rapidly [1] and overpopulation needs food more than ever in order to survive, food production also become an important industry. But, energy efficient food production is not yet really achieved and dairy products are not an exception. For this reason, the production with the efficient use of energy has been the subject of many academic fields, especially in industry especially in recent years [2,3,4].

Yoghurt producing facilities that are running in Turkey are usually using conventional methods that are consuming much more energy than the process would consume. Using fossil fuels for heating process also emitting CO_2 and wasting heat. Since used coals are not

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atomized, efficient combustion also is not possible. It is reported that, during flavored yoghurt production exergy loss can rise up to 26% [2].

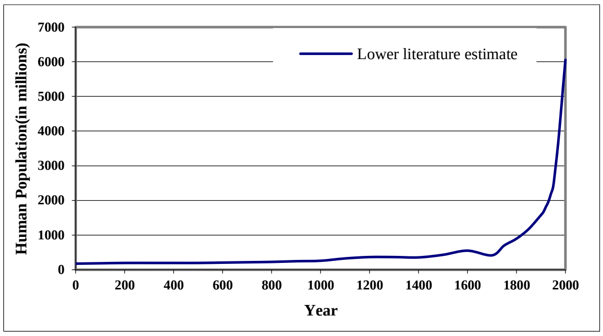

Figure 1. Human Population Increasement

Conventional incubation and post-cooling systems have problems such as non-sensitive temperature control and high energy consumption. The proposed solution to these problems is the use of heat pump technology because the heating and cooling processes in the yoghurt production process are carried out in series. The heat pump system can be used for preheating in high temperature applications and also can work efficiently at medium to low temperatures (below the first freezing point of the material). Heat pumps are high-performance systems for converting electrical energy into heat energy, achieving optimum efficiency, especially when the difference between source and supply temperatures decreases. Heating and cooling can be provided with a single device.

Yoghurt production is a set of processes with high energy consumption and water density. The required energy is mainly used for pasteurization, cooling and homogenization. The water is consumed for heating, cooling and mix preparation processes during yoghurt production [5]. Considering that the cooling process takes longer than heating, more capacity is required for cooling, 8,000 L/h for cooling the yoghurt, 40,000 L/h of chilled water is required [6].

The United Nations Environment Program (UNEP) estimated that the needed amount of electricity for production of the milk was 0.2 MJ per kg of milk, based on this Dewick et al. (2007), estimated that 1.2 MJ per kg yoghurt is required [7]. As it can be seen, there is an intensive use of energy in yoghurt production. In this sense, energy efficient incubation systems are one of the important research topics. Also, rapid heating-cooling will damage the product in the incubation and cooling room. For this reason, the temperature will be increased and decreased sensitively with the heat pump system [7]. Studies using heat pump for heating and/or cooling process is presented Table 1.

Yoghurt producing is accomplished in 11 stages, which starting from milking stage and ends at cooling stage. But this paper interests only last two stages which are incubation and cooling stages. But the standardization process also has great influence on the final product because of the fat content of the milk in fluences properties of the yoghurt; increase in the consistency and viscosity of yoghurt increases as the fat increases [17-18].

Incubation is the a phase where starter kit bacterias get injected to the pasteurized milk. After the injection, this incubated milk will be kept under steady conditions for 3 to 5 hours depends on the bacteria type.

Table 1. Summary of previous studies about drying, heating and cooling using heat pump technology

Ref.	Application	Refrigerant	Purpose	Performance indicator
[8]	Industrial scale drying with heat pump		Drying of seedless grapes	COP_{system} 2.81
[9]	Drying with solar assisted heat pump		Drying of red pepper	COP_{system} 2.10
[10]	Small scale drying with heat pump		Drying of grape pomace	COP_{system} 3.28 (45 °C&1m/s) 3.10 (50 °C&1m/s)
[11]	Heating	R134a R410a	Residential sector	T_{in} = 20 °C T_{out} = 0 °C COP= 2.7 T_{in} = 20 °C T_{out} = 5 °C COP= 3.2 T_{in} = 20 °C T_{out} = 10 °C COP= 4.5
[12]	Heating	-	Space heating	Mean value ASHPs COP= 2.59; SD-GHPs COP = 3.72; SWHPs COP= 4.64; MD-GHPsCOP= 5.15
[13]	Heating	CO2/ [BMIM][PF6]	Produce heat isothermally at the temperature over 120 °C	Source 290K-Sink 400K COP 2.16
[14]	Simultaneously heating & cooling	R407C CO_2	Hotels, luxury dwellings and smaller office buildings	First law COP COP_{R407C} 3.57 COP_{CO2} 3.26
[15]	Air source heat pumps for space heating &cooling	-	Space conditioning	Seasonal COP 2.32 - 3.44
[16]	Simultaneously heating & cooling	R407C R290	Collective residential buildings	7/55 simultaneous mode (cooling/heating) COP_{R407C} 5.79 COP_{R290} 5.40

These parameters are given as follows: air quality of incubation room, steady incubation temperature, homogenous heat distribution. Göçer et al. [20] tried different incubation temperatures and finished the process at different pH values for one selected probiotic bacteria. They observed that best physicochemical properties obtained at 45°C incubation temperature. Lee and Lucey [21] also studied on incubation temperature and found that incubation temperature should be 45 °C for a selected bacteria. Wardani et al. [22] observed that best incubation temperature for L. Plantarum Dad 13 is 37 °C in terms of acidity and curd formation. Aswal et al. [23] researched the rheological, physicochemical properties of yoghurt with the change of substances.

Cooling of yoghurt is the last stage of the production. Yoghurt should not be cooled instantly but cooling has to take almost 24 hours. Instantly cooled yoghurts will have cracked structure, which is not acceptable. Cooling temperature has to be 2-4 °C [6] depending on these parameters in order to achieve quality products. Quality design of the incubation room and the cooling room is essential for achieving this task. Ice thermal storage is an energy efficient method for the cooling process. Ice thermal storage units storing the latent heat and offering intensive storage capacity.

In this study, the extracted heat from the ice storage tank was used to heat the incubation (fermentation) room. Since extracting heat from the ice storage tank decreases the temperature inside the tank, it makes ice storage is possible. Since ice storage can be done, it is also possible to cool the cooling room with the stored ice.

This paper claims that this new approach would reduce energy consumption and this approach would be beneficial for both yoghurt producing facilities and nature due to reduced energy consumption and efficient use of energy.

2. METHODOLOGY

In conventional yoghurt producing facilities, required heating and cooling process are applied independently. In order to reduce energy consumption, cooling and incubation rooms are connected via the combined system. This system extracts heat from ice storage tank and heats the incubation room with the condenser. Since this system works with Reverse Carnot Cycle, a logP-h diagram of the system can be seen at Figure 2.

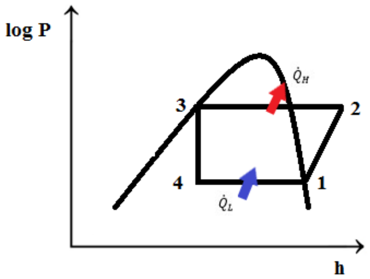

Figure 2. The logP-h diagram of the system working between incubation room and storage tank.
$\dot{\boldsymbol{Q}}_L$refers to the heat drawn from the ice storage tank and $\dot{\boldsymbol{Q}}_H$ refers to the heat thrown into the incubation chamber.

Designed incubation room to have laminar flow conditions inside, Reynolds number can be calculated as following equation:

$$Re = \frac{\rho v L_c}{\mu} \tag{1}$$

To calculate convection heat transfer coefficient, Nusselt number can be expressed as below:

$$Nu = \frac{h L_c}{k} \tag{2}$$

Total heat losses of incubation roomcan be determined with the following equation:

$$\dot{Q} = UA\Delta T \tag{3}$$

And the coefficient of performance of heat pump can be obtained from:

Where:

$$COP = \frac{\dot{Q}_{cond}}{\dot{W}_{comp}} \tag{4}$$

$$\dot{Q}_{cond} = \dot{m}\,\Delta h \tag{5}$$

$$\dot{W}_{comp} = \dot{m}\,\Delta h \tag{6}$$

Ice storage is a phase change problem. Therefore this problem can be modeled as Eq.7 and solved as following: Since this cooler is a solution, there are 3 stages depending on the liquid fraction (ø). The first stage is where both the base fluid and the coolant is liquid, the second stage is where the base fluid is liquid but the coolant is solidifying and the third stage is where the coolant is solid. These phases are depending on the melting temperature of the coolant and the working temperature of the base fluid.

$$Q = \begin{Bmatrix} if\ \emptyset = 0, & Q = m_{bf}c_{p,bf}\Delta T_{bf} + m_{pcm}c_{p,f}\Delta T_{pcm} \\ if\ 0 < \emptyset < 1, & Q = m_{bf}c_{p,bf}\Delta T_{bf} + m_{pcm}L \\ if\ \emptyset = 1, & Q = m_{bf}c_{p,bf}\Delta T_{bf} + m_{pcm}c_{p,s}\Delta T_{pcm} \end{Bmatrix} \tag{7}$$

Table 2. Carnot and first law performance factors depending on the operating mode [14].

Performance Factor	Heating mode (Op.1)	Cooling mode (Op.2)	Dual mode (Op.3)
First law COP, COP_f	$\frac{Q_H}{W_{comp}}$	$\frac{Q_L}{W_{comp}}$	$\frac{Q_H + Q_L}{W_{comp}}$
Carnot COP, COP_c	$\frac{T_{hot\ source}}{T_{hot\ source} - T_{cold\ source}}$	$\frac{T_{cold\ source}}{T_{hot\ source} - T_{cold\ source}}$	$\frac{T_{hot\ source} + T_{cold\ source}}{T_{hot\ source} - T_{cold\ source}}$

Ice storage offers intensive cooling capacity and it is usable for this application. The coolant is an aqueous solution, therefore, it is possible to circulate it inside the cooling room using a heat exchanger with a pump.

3. INCUBATION ROOM DESIGN

Designing of the incubation process is a specific task. In presented design, there are two separate rooms as incubation and cooling room. After end of incubation process, the products taken to the cooling room. Schematical view of the incubation rooms is given in Figure 3. Ventilation inlet units are placed at the bottom of the left and right side of the room and the pressure outlet unit is placed at the top middle of the room in order to have homogenous flow and heat distribution inside the room. Air inlet units have high-efficiency particulate absorber (HEPA) filters to prevent contaminant particles inside the incubation system.

Ice thermal storage unit is located near the incubation room. This unit is filled with base fluid and ice balls. Ice balls are basicly plastic balls which has phase changing liquid inside. When the evaporators are extracting heat from the base liquid, the fluid inside the ice balls is solidifying and storing latent heat. Since base fluid has the lower phase change temperature, only the fluid inside the balls are solidifying and for that reason, a working liquid with a phase change material advantage can be obtained. Standard phase change material (PCM) applications do not offer working fluid coolant but this approach has this great benefit [24-25].

Cooling room is also located very near to the incubation room due to prevent structural problems during transporting the yoghurt carrying carts. This room is also insulated to prevent heat transfer from the room. Inside the room, cold water is circulated via a pump using a heat exchanger to cool the system air for cooling of incubated yoghurt. Consequently, a combined energy efficient system was designed and presented in Fig. 3.

R410a and as an option R134a were chosen as the refrigerants in the heat pump unit since they provide suitable operating temperatures (2-45 °C) for the production of yoghurt. However, both refrigerants are frequently used in industrial heat pump application, both offers the lowest ASHRAE toxicity classification "A1" with essentially zero ozone depletion potential (ODP) and global warming potential values (GWP) 2088,1430.

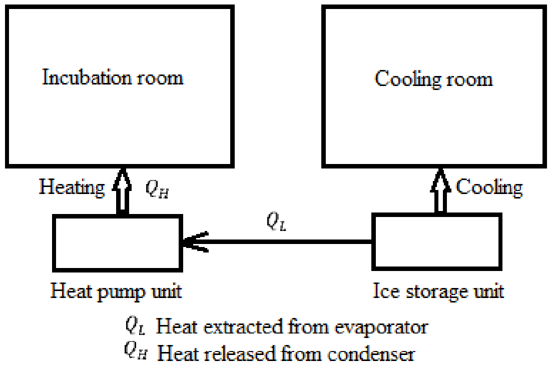

Figure 2. Design of the combined heating and cooling system

4. RESULTS AND DISCUSSION

In this study, a combined system which includes both heating and cooling in yoghurt production has been designed. The performance coefficients of the heat pump shown in Figure 2 were analyzed according to the first law and Carnot and are shown in Table 3.

As can be seen from Table 3, COP values are calculated in case of heating, cooling and dual operation. Since both heating and cooling can be done for two groups of products at the same time, it would be more appropriate to evaluate the COP value of this system as dual. s a result of the product process, incubation takes place first, while heating is carried out at the same time, the heat extracts from the ice storage tank. With the presented design, both heating and cooling processes can be carried out simultaneously and/or independently from each other, so that energy is stored at a rate of 64/100 for R410a and a rate of 68/100 for R134a ($COP_{cooling}/COP_{heating}$) compared to the heat given independently of the incubation time.

Based on the 1 kWh heating load, the electrical energy requirement for R410a and R134a will be 0.353 and 0.316 kWh, respectively and this corresponds to 0.144 and 0.129 TRY in Turkey (kWh price of electricity is accepted as 0.41 TRY). In addition, energy costs are calculated as 0,193 and 0,367 TRY, respectively, when natural gas and fuel oil are used in a 90% efficient boiler for this heating load (the lower heating value of natural gas and fuel-oil are taken as 8250 kcal/m^3 and 9200 kcal/kg and unit fuel prices are accepted as 1.67 and 3.93 TRY, respectively).

Table 3. Results for incubation-cooling system according to first law COP and Carnot COP

Refrigerant	T_H (°C)	T_L (°C)	η_{ise} (%)	$COP_{f,Op.1}$	$COP_{f,Op.2}$	$COP_{f,Op.3}$	$COP_{c,Op.1}$	$COP_{c,Op.2}$	$COP_{c,Op.3}$
R410a	55	-10	80	2.83	1.83	4.65	5.04	4.04	9.09
R134a				3.16	2.16	5.31			

Considering the cost of fuel, the heat pump seems to be more profitable, and in addition to the operating and maintenance costs, the heat pump becomes even more advantageous. Since heating required for the incubation process can be extracted from the ice storage tank, it is also possible to use the stored energy (phase change material) during heating for the cooling load. Thus, a cost-free cooling process is provided and this provides the user with a profit in every aspect.

In this system, which is particularly recommended for industrial plants, energy can be stored on ice when energy demand and electricity pricing is low (especially at night in Turkey 10:00 pm – 06:00 am). The cooling process in food facilities has a more important place in terms of health and product quality. Heat extracts from the ice storage tank and the ice is produced and heat is supplied from the condenser. Since the cooling process is more energy-intensive than heating, waste heat can be utilized in both single and dual operation modes. The waste heat can be used as a hot source/water in accordance with business needs or, it can be used for clening in place (CIP) process which is one of the most important subjects of food factories, so that the hot water can be brought to a lower energy consumption and the desired CIP temperature in a faster time.

In industrial applications, the heating and cooling applications usually performed in two different places with two different thermal systems. With presented design, these heating and cooling applications can be performed in two place again but this time with only thermal system. The study on the design of the incubation room was intended to assist others to work on this issue, and some recommendations were made as to the direction in which the study could proceed.

5. ACKNOWLEDGEMENT

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Nomenclature

A : Heat transfer area (m^2)

$c_{p,bf}$: Specific heat of base fluid (kJ/kgK)

$c_{p,f}$: Specific heat of phase changing fluid (kJ/kgK)

$c_{p,s}$: Specific heat of phase changing material in solid phase (kJ/kg K)

h : Convection heat transfer coefficient (W/m^2K)

k : Thermal conductivity of the material (W/mK)

L : Latent heat (kJ/kg)

L_c : Characteristic length (m)

m_{bf} : Mass of base fluid (kg)

m_{pcm} : Mass of phase changing fluid (kg)

$\dot{m}$: Mass flow rate of refrigerant (kg/s)

Nu : Nusselt number

$\dot{Q}_{cond}$: Energy released at condenser (kW)

PCM : Phase change material

Re : Reynolds number

U : Overall heat transfer coefficient (W/m^2K)

v : Velocity of the fluid (m/s)

μ : Dynamic viscosity (Pa.s)

ρ : Density (kg/m^3)

$\dot{W}_{comp}$: Energy consumed by compressor (kW)

Δh : Entalpy difference of refrigerant (kJ/kg)

ΔT : Difference in temperature (K)

ΔT_{bf} : Temperature difference of base fluid (K)

ΔT_{pcm} : Temperature difference of phase changing fluid (K)

Q_H : Heat thrown into the incubation chamber (kJ)

Q_L : Heat drawn from the ice storage tank (kJ)

COP : Coefficient of Performance

Subscripts

in : inlet

out : outlet

H : heatsink

L : heat source

comp. : compresor

ise : isentropic

f : first law

c : carnot

Op.1 : Operation mode 1

Op.2 : Operation mode 2

Op.3 : Operation mode 3

Abbreviations

ASHPs : Air source heat pump systems

SD-GHPs : Conventional GCHP (ground-coupled heat pump systems)

SWHPs : Surface water heat pump systems

MD-GHPs : Medium-depth geothermal energy

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