Application of Stirling Cooler to Food Processing: Feasibility Study on Butter Churning

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Abstract

The Stirling cycle engine was invented almost 190 years ago. In this study, the reverse Stirling cycle is investigated for use in refrigeration. This type of cycle is referred to as Stirling cooling or cooler. An experimental free-piston Stirling cooler (FPSC) was constructed and the effects of the device parameters in relation to the performance of the cooler were studied; the equipment was then experimentally applied to churning butter. Two effect parameters, namely, the size of the displacer involving heat regeneration and the volume of the working fluid (air) were studied. The results indicated that a larger displacer resulted in a lower temperature in the cooler. When the working fluid volume was large or the compression ratio was high, the cooling effect was enhanced. It was concluded that by churning butter using the Stirling cooler, coagulation of the butter occurred more rapidly than when the contral was used in the process; the water content of the butter obtained was lower and the fat content was higher using the Stirling cooler. This implies that the feasibility of using the Stirling cooler for churning butter is high.

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Keywords: Stirling cooler, device parameters, displacer, working fluid, butter churning

1. Introduction

The Stirling engine was invented by Robert Stirling in 1816 (Walker, 1980). Stirling engines are powered by expansion when the gas is heated, followed by compression of the gas when it is cooled. There are four processes: expansion under an isothermal condition, refrigeration under a constant volume condition, compression under an isothermal condition, and heating under a constant volume condition. The entire process described above is called the Stirling cycle. The Stirling engine system has a constant high efficiency and low noise in comparison to the conventional internal combustion system, such as the gasoline or diesel engine.

On the other hand, the reverse Stirling cycle is used for refrigeration. This type of cycle is referred to as Stirling cooling. (The details of the thermodynamics of the Stirling cooling cycle will be introduced later using a P-V chart). The cooling system contains an acceptor, a rejector, working fluid, a piston and displacer, and a regenerator. For example, a free-piston Stirling cooler (FPSC)* is a single-phase cooling device that transfers heat from a cool source to a warm sink with the help of external heat exchangers. The Stirling cooling system has many advantages. For example, the working fluid of the Stirling cooler can be air, helium or hydrogen, which have zero ozone depletion potential (ODP) and zero global warming potential (GWP) in contrast to common refrigerants such as CFCs, HCFCs or HFCs, which are characterized by

* http://www.globalcooling.com/howitworks.html (Aug.20, 2005)

ODP or GWP. Also, the Stirling cooling cycle can be used over a wide temperature range and has a theoretically high efficiency.

It is known that in some methods of food production, refrigeration and mixing are essential. For example, the process of butter production involves a considerable number of stages. These include raw milk storage, cream separation, pasteurization, controlled cooling and continuous butter churning, etc (Kawada, 2004). Thus, in the process of producing butter, there is a step in which the cream is churned up and simultaneously refrigerated. It is known that in the Stirling cooler with colliding displacers (SCCD) (Kobayashi & Matsuo, 2005), the cylinder concusses regularly to produce cooling and churning actions. Further, when producing butter, the cream needs to be churned up and refrigerated simultaneously to enhance fat coagulation. In this study the relationship between the refrigerant properties of the Stirling cooler and the churning characteristic of cream is investigated to determine the feasibility of using the cooler in dairy processing.

Many researchers have studied the Stirling cycle engines with regard to their application and have found that there are many factors affecting the performance of these Stirling cycle engines, for example, the volume of the working gas, oscillation frequency, size of displacer, material of regenerator, regenerator effectiveness, volume compression ratio (Rallis, Urieli & Berchowitz,1977; Rifkin, Vincent & Benson,1980; Chen & Griffin,1983) etc., and the performance of the Stirling cycle engines was also discussed such as power output and thermal efficiency (Dochat, Moynihan & Dahr,1980;

Vincent, Rifkin & Benson,1980). Refering to the Stirling cycle cooler, in the 1950s, the Philips Company provided Stirling coolers as air liquefiers for the commercial market (Walker, 1983a). In the 1990s, Global Cooling BV and Sunpower, Inc. (Mennink & Goossen, 1995) developed a free-piston Stirling cycle cooling system that could be powered by both electricity and solar photovoltaic systems and was suitable for use in domestic refrigeration cabinets. Park, Hong, Kim, Koh, Kim, Yu, et al. (2002) discussed the effect of the charging pressure and operating frequency on the performance of the Stirling cooler and found that at a low frequency, the cooler response was dominated by the characteristics of the mechanical spring, however, at a high frequency, the cooler was controlled by the characteristics of the gas spring.

From the above descriptions, it can be concluded that many factors can affect the performance of the Stirling cycle cooler. When an FPSC is designed, influential factors must be taken into consideration And in food processing some aspects must be noticed, such as saving energy and protecting the environment. In this study, an experimental FPSC was constructed and the effects of device parameters on the performance were studied; the equipment was then tested for churning butter. The results are utilized to design and operate an improved Stirling cooler that can be used for food processing with energy saving and environment-friendly.

2. Material and Methods

2.1 Experimental set-up

Fig. 1-1 shows a sketch of the experimental FPSC. The power unit is an oscillating machine 1 (RYOBI, JSE-60) which is controlled by a transformer 8 (Tokyo Rikosha, PSD5A). By adjusting the transformer, the oscillating frequency can be easily controlled. The glass injector 3 (100 ml) is composed of a piston and a sleeve. The piston of the injector is fixed to the bracket 10; however, the sleeve can move up and down freely along with the piston at a certain amplitude. The glass cylinder 5 (ID: 35 mm; OD: 37 mm; L: 100 mm) is connected to the sleeve of the glass injector by the rubber plug 4. When the oscillating machine is operational, through the adjustable rod 2, it drives the sleeve of the glass injector and the connected glass cylinder to move up and down along with the piston of the injector. There are a few holes on the adjustable rod that can be used to adjust the working fluid volume in the injector and cylinder. Because the displacer 6 (steel wool) simultaneously working as the regenerator, is not connected to the cylinder, it also oscillates asynchronously along with the cylinder. Accordingly, the working fluid in the cylinder is alternately compressed and expanded by the piston. According to the thermodynamics of the Stirling cycle (which will be discussed later), the temperature of the cylinder tip (cold head) will decrease, and simultaneously, that of the opposite side of the cylinder (warm head) will increase. In order to improve the motion of the displacer, a mechanical spring is added to each end of the displacer (Kobayashi, 2003).

It should be noted that the correlation between the diameter of the displacer and the inner diameter of the cylinder is very important. A close correlation is essential. If the diameter of the displacer is too large, oscillation will be difficult. In contrast, if the diameter of the displacer is too small, the working fluid will pass through the gap (between the displacer and the cylinder) rather than passing through the regenerator incorporated in the displacer.

A plastic bottle 7 was connected to the glass cylinder in the butter churning experiment. The cream was filled into the plastic bottle which oscillated simultaneously with the glass cylinderto churn the cream.

Fig. 1-2(a) shows the cycle of the ideal FPSC and Fig. 1-2(b) shows the P-V chart of the ideal Stirling cooling cycle. The ideal Stirling cooling cycle is composed of four completely reversible processes. Process 1-2 involves constant volume regeneration; in this process, internal heat transfer occurs from the working fluid to the regenerator. Hence, the temperature of the working fluid is reduced from T_C to T_E. Process 2-3 involves constant temperature expansion; in this process, the working fluid is expanded to absorb heat energy from the surroundings, so that the temperature of the surroundings decreases, however, the temperature of the working fluid remains constant at T_E. Because the temperature of the surroundings decreases, this process can be called cooling. Process 3-4 involves constant volume regeneration; in this process, internal heat is transferred from the regenerator back to the working fluid. Hence, the temperature of working fluid increases from T_E to T_C. Process 4-1 involves constant temperature compression; in this process, the working fluid is compressed, so that heat energy is transferred to the external sink. In this process, the temperature of the working fluid remains constant at T_C.

2.2 Effect of device parameters on FPSC performance

There are many parameters that can affect the performance of the equipment. In this paper, two major effect parameters—the size of the displacer and the volume of the working fluid (air)—were studied.

First, the effect of the size of the displacer on the performance was investigated. In the experiment, the volume of the working fluid (air) was kept constant, while three different sizes of displacer were tested, Φ35 × 35 mm, Φ35 × 45 mm and Φ35 × 55 mm, and the temperature of the cold head was recorded. In order to measure the temperature of the cold head it must be insulated from the environment, therefore, styrene foam was wrapped around the tip side of the cylinder, while the opposite side or the warm head was left exposed to the environment. The temperature change of the cooler was measured with a T-type thermocouple and recorded on a personal computer at intervals of 3 s using a software-controlled thermal data acquisition system (E830). According to the preliminary test on the process stability, the frequency of the oscillating machine was maintained at approximately 12 Hz. The test was stopped when the temperature did not change, i.e. steady state achieved.

The effect of the volume of the working fluid (air) on the performance was then investigated. In this experiment, the best displacer (determined from the former experiment) was used and the working fluid (air) volume was changed as 50, 70, and 100 ml, and the cooler temperature was recorded until it reached the steady state. The frequency of the oscillating machine was approximately 12 Hz. The ambient temperature was approximately 24°C for all of the tests.

2.3 Determination of temperature falling rate

On the basis of the time course of the temperature, the temperature falling rate was calculated using equation (1):

$$R(t) = -\frac{dT}{dt} = -\lim_{\Delta t \to 0} \frac{T(t+\Delta t) - T(t)}{\Delta t} \quad \cdots\cdots \quad (1)$$

where *R(t)* represents the temperature falling rate at time *t* (°C/s); *T(t)*, the temperature at time *t* (°C); *t*, the operating time (s). Because the temperature decreased, the negative value of *R(t)* was used.

The software “OriginPro 7” was used to calculate the temperature falling rate.

2.4 Application of cooler for churning butter

After the optimal parameters which affect the performance of the FPSC were determined, butter churning was experimentally carried out. Churning is the process of shaking up whole milk or cream to produce butter. The initial churning temperatures were 10, 20, and 30°C. .

First, pure fresh cream (Takanashi, content of fat: 35%) was adjusted to the required temperature, and then placed into the plastic bottle for churning. When the FPSC was operational, the plastic bottle would oscillate up and down with the glass cylinder, so that the cream was churned and simultaneously refrigerated. Every 1 or 2 minutes, the quality of the non-fat milk that remained in the bottle was measured intermittently. That is to say the liquid part of the cream was extracted from the plastic bottle during the pause when the equipment was stopped. After the liquid was weighed, it was filled back into the cream bottle and churned again. The temperature of the cream was recorded using a thermosensor thermometer (Chino, MR2041-MV) and the temperature measuring point was at the bottom of the plastic bottle. The churning test was stopped when the quality of the non-fat milk remained unchanged. According to the preliminary investigation, the optimum frequency of the oscillating machine was determined to be approximately 14 Hz. The ambient temperature was 24°C, and the plastic bottle was not covered by adiabatic material. Two tests were carried out for each initial churning temperature. In one test, the displacer was used to produce cooling and in the other, the displacer was not used as the control experiment, which implied that there was no cooling effect.

The water and fat content of the butter were measured by a currently used method (The Pharmaceutical Society of Japan, 1999).

3. Results and Discussion

3.1 Factors affecting the performance of FPSC

Fig. 2 shows the effect of the displacer size on the cooler performance when the working fluid volume is 100 ml. When the displacer size is Φ35 × 55 mm, the temperature decreases from 24°C to –10°C after the FPSC has been in operation for 400 s. This decreasing tendency of the temperature was also reported by Oguz and Ozkadi (2000). Fig. 2 also shows that displacer sizes of Φ35 × 35 mm or Φ35 × 45 mm reduce the refrigeration effect compared to that obtained with the Φ35 × 55 mm displacer. After the FPSC has been operational for approximately 800 s, the temperature stabilizes at –14°C in the case of the best performing displacer.

Fig. 3 shows the change in the temperature falling rates with time for a working fluid volume of 100 ml. Irrespective of the displacer used, there is an initial short rising phase of approximately 1 min, followed by a falling phase of the temperature falling rate. When the size of displacer is Φ35 × 55 mm, the highest temperature falling rate is approximately 0.175°C/s, and the temperature falling rate is higher than that of the other two stations for most of the working time. The reason for the peak value may be that along with the rise in the temperature of the warm head, the inner energy of the working fluid in the warm head accumulates and the temperature gradient between the warm head and cold head gradually increases, thus reducing the initial refrigeration capability. It is also possible that inadequate insulation of the cylinder caused a decrease of the temperature falling rate.

From the above discussions, the conclusion obtained from Figs 2 and 3 is that the size of the displacer has a significant impact on the performance of the cooler. Thus, the Φ35 × 55 mm displacer was selected for the following experiments.

Fig. 4 shows the effect of the volume of the working fluid on the performance of the cooler when the Φ35 × 55 mm displacer was used. When the FPSC has been operational for approximately 800 s, the temperature reaches a steady state. When 100 ml of working fluid is used, the refrigeration effect is better than that achieved when the volume is set at 70 or 50 ml. For example, after 400 s, the temperature is approximately

–10, –8, and –2°C for working fluid volumes of 100, 50, and 70 ml, respectively. This implies that the larger the volume of working fluid, the lower the temperature of the cooler. It is known that at certain temperatures, a certain volume of gas (working fluid) has a fixed specific heat, and when the temperature and/or pressure changes, it will absorb or release a defined quantity of energy (Walker, 1983b; Yamashita, Hamaguchi, Kagawa, Hirata, & Momose, 2005). Larger volumes of working fluid will absorb or release more energy; hence, more energy can be transmitted out of the cooler which will then acquire a much lower temperature.

There may be three explanations for the fact that the temperature cannot be reduced unceasingly. The first is related to the thermal capacity of the regenerator, which is not of sufficient size to transport energy. The second explanation is that the thickness of the spumy plastic which was used as an adiabatic material in this test may have caused a loss in energy and the third explanation may lie in the fact that the warm head cannot radiate heat adequately.

Fig. 4 also shows that when the volume of the working fluid is 50 ml, the refrigeration effect is better than that obtained when the volume is 70 ml.

Generally, the Coefficient of Performance (COP) of cooler is used as a measure of the refrigeration effect: the higher the COP, the more efficient the cooler. Equation (2) shows the relationship between the COP and the working conditions of the Stirling cooler (Walker, 1983c):

$$COP = \frac{1}{(\gamma - 1)}\left[\frac{(\gamma - 1)\ln r - (\tau - 1)(1 - \varepsilon)}{(\tau - 1)\ln r}\right] \quad \cdots \quad (2)$$

where COP represents the Coefficient of Performance of the Stirling cooler; γ represents the ratio of specific heat (for air, γ =1.4); τ represents the ratio of the warm head temperature T_C and cold head temperature T_E, that is, $\tau = T_C / T_E$; ε represents the regenerator effectiveness (generally, $\varepsilon < 1$); and r represents the compression ratio or the ratio of the expanded volume V_E and compressed volume V_C, that is, $r = V_E / V_C$.

The above equation shows that at certain temperatures of the warm and cold head when the gas (working fluid) is compressed at a higher compression ratio, the COP of the cooler increases. For the experimental equipment, the compression volume of each test is constant; hence, when there is a change in the volume of the working fluid, the compression ratio will also change. The smaller the volume of the working fluid becomes, the greater the compression ratio is obtained. Because the compression ratio is higher when the volume of the working fluid is 50 ml as opposed to 70 ml, the refrigeration effect is greater when the former volume is used. For example, if the other conditions remain constant (assuming that τ = 1.2 and ε = 0.7), the compression ratio for 50 ml of working fluid is 1.8 and that for 70 ml of working fluid is 1.4, thus the COP can be calculated as COP_{50} =3.7 and COP_{70} =2.8 respectively using equation (2). The model derived from equation (2) explains the experimental results observed, i.e. a better refrigeration effect is achieved using 50 ml of working fluid rather than 70 ml.

Fig. 5 shows the change in the temperature falling rate with time when the Φ35 × 55 mm displacer is used; there is a short initial rising phase of about 1 min, followed by a falling phase. Apparently, according to the temperature falling rates, Fig. 5 can corroborate the conclusion of Fig. 4.

Hence, the conclusion that can be drawn from Figs. 4 and 5 is that enhancement of the cooling effect is achieved with a large volume of working fluid or a high compression ratio.

3.2 Discussion of the butter churning experiment

Fig. 6 shows the typical change of temperature which occurs during the churning processing when an initial temperature of 30°C is used. In general, at a temperature of 30°C, milk separates into cream and skimmed milk under centrifugation. Fig. 6 shows that the temperature of the cream under the Stirling cooler is lower than that achieved under the control condition. After 40 minutes, the temperature of the cream under the cooler was reduced by 8°C from 30°C to 22°C; however, the temperature under the control experiment was reduced only by 2°C from 30°C to 28°C. Since the temperature was measured at the bottom of the bottle containing the cream and because this point is remote from the cylinder of the cooler, it is to be expected that the recorded temperature will be higher than that in the vicinity of the cooler. When cream is generally churned at a temperature of 12–15°C, the dairy fat will aggregate to form a cluster called the butter cluster (Kawada, 2004); therefore the temperature in proximity to the cylinder would be considered suitable for the butter churning process.

Fig. 7 shows the change in the quality of non-fat milk with time. Comparing the Stirling cooler and the control it can be seen that the butter cluster forms earlier when the former method is used. When the initial temperature was 30°C, butter churning in the Stirling cooler was almost complete in 5 min, however, under control condition the process required 8 min. A total of 20 g of non-fat milk was produced when the churning procedure was carried out under the Stirling cooler, while only 9 g was produced using the control method despite the fact that 60 g of raw material was used in both experiments. This implies that the quality of butter produced under the Stirling cooler was better than that obtained using the control method because more non-fat milk was extracted to obtain a more dense butter cluster.

Table 1 shows the water and fat content of the butter cluster at different initial temperatures. When the cooler was used, the water content of butter cluster was 27–29% and the fat content 68–69%. However, under the control condition, the water content of the butter cluster was 48–58% and the fat content 37–47%. Therefore, butter cluster produced using the Stirling cooler is lower in water content and higher in fat content than that produced using the control method.

From the above results it is clear that the Stirling cooler which is capable of refrigerating material and churning it synchronously, will accelerate the formation of the butter cluster. This suggests that using the Stirling cooler to produce butter is a highly feasible option. However, the fat content of the butter is more than 80% (Kawada, 2004; Hayashi, 1992). Therefore, ameliorations of this equipment such as the change of material or adjustment of specification of the displacer, or the improvement of heat insulation are necessary to obtain butter with a high quality.

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Figure Captions:

Fig. 1-1 Sketch of the experimental set-up: a free piston Stirling cooler. 1, oscillating machine; 2, adjustable rod; 3, injector; 4, rubber plug; 5, glass cylinder; 6, displacer (simultaneously working as the regenerator); 7, plastic bottle; 8, transformer; 9, AC power supply; 10, bracket.

Fig. 1-2 The ideal FPSC cycle and its P-V chart. (a) The ideal FPSC cycle. The thick lines represent the location of the piston and the displacer. (b) P-V chart of the ideal Stirling cooling cycle. T_C is the temperature of the compressing region; T_E is the temperature of the expanding region. The ideal Stirling cooling cycle is made up of four totally reversible processes: process 1-2 is the constant volume regeneration; process 2-3 is the constant temperature expansion; process 3-4 is the constant volume regeneration; process 4-1 is the constant temperature compression. In process 2-3, the working fluid absorbs energy from the surroundings reducing the temperature of the surroundings and thus producing a cooling effect.

Fig. 2 The effect of the displacer size on the cooler performance. Displacer size: –□–, Φ35×35 mm; –■–, Φ35×45 mm; –▲–, Φ35×55 mm.

Fig. 3 The temperature falling rate with time. Displacer size: –□–, Φ35×35 mm; –■–, Φ35×45 mm; –▲–, Φ35×55 mm.

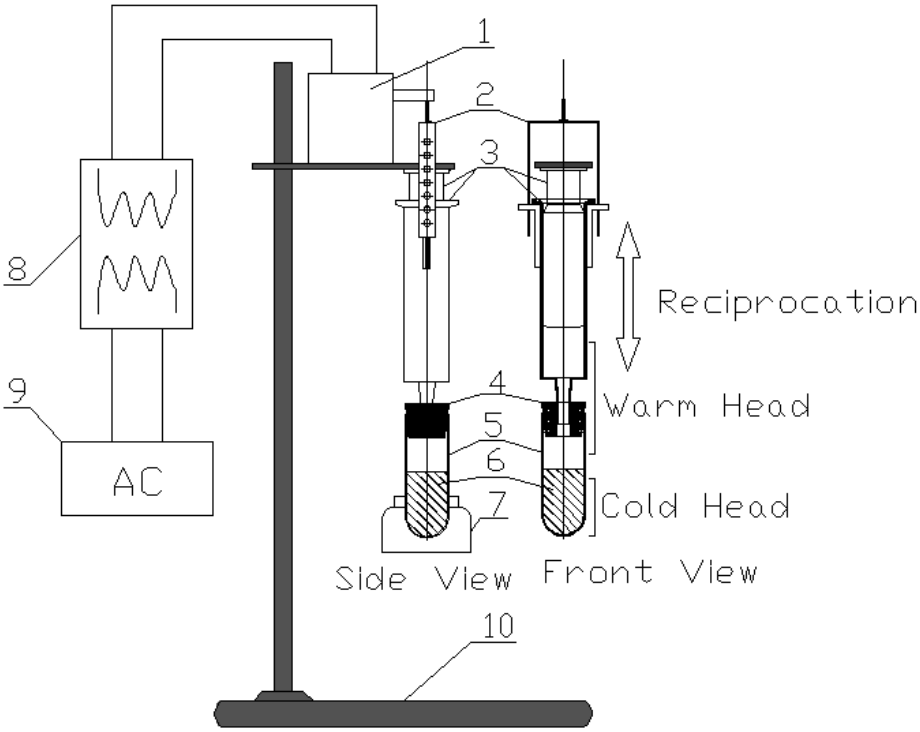
Fig. 4 The effect of the volume of working fluid on the cooler performance when the Φ35 × 55 mm displacer was used. Volume of working fluid: –■–, 50 ml; –□–, 70 ml; –▲–, 100 ml.

Fig. 5 The temperature falling rate with time. Volume of working fluid: –■–, 50 ml; –□–, 70 ml; –▲–, 100 ml.

Fig. 6 Change of the cream temperature with time during the butter churning process when an initial temperature of 30°C was used. –◆–, Cooler; –■–, Control.

Fig. 7 Change in the quality of the non-fat milk with time during the butter churning process. –◆–, Cooler; –■–, Control.

Fig. 1-1



1
2
3
8
Reciprocation
9
4
Warm Head
5
AC
6
Cold Head
7
Side View
Front View
10

Fig. 1-2

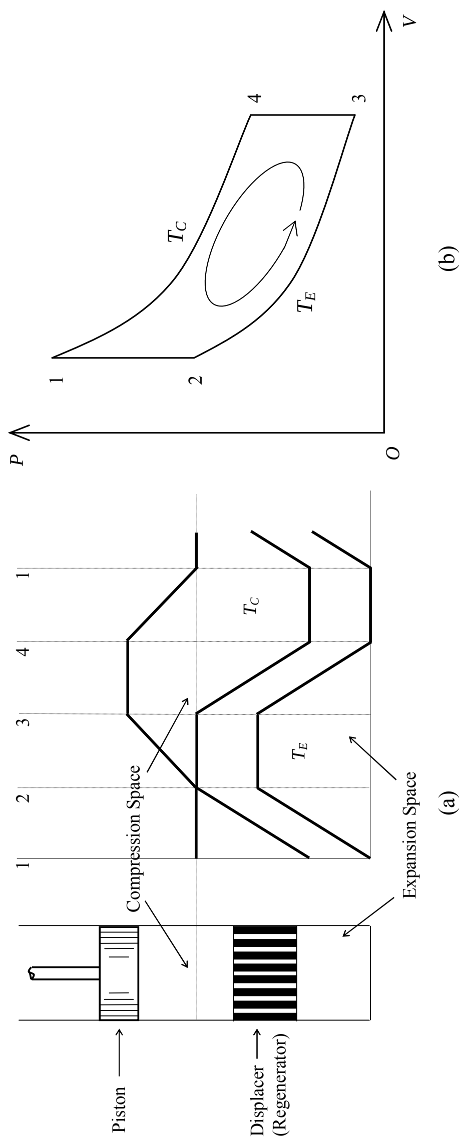
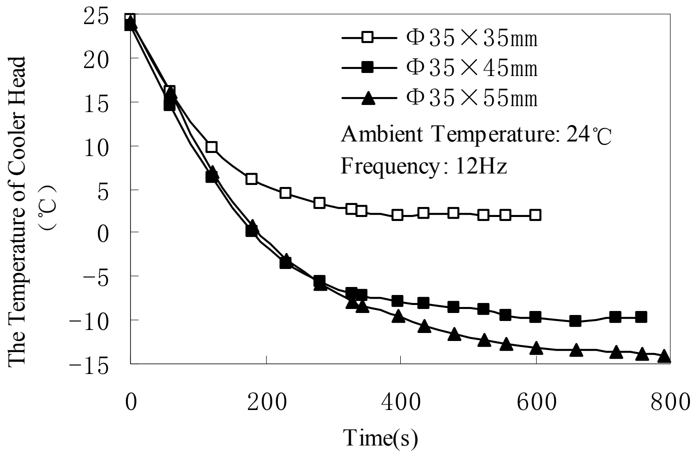
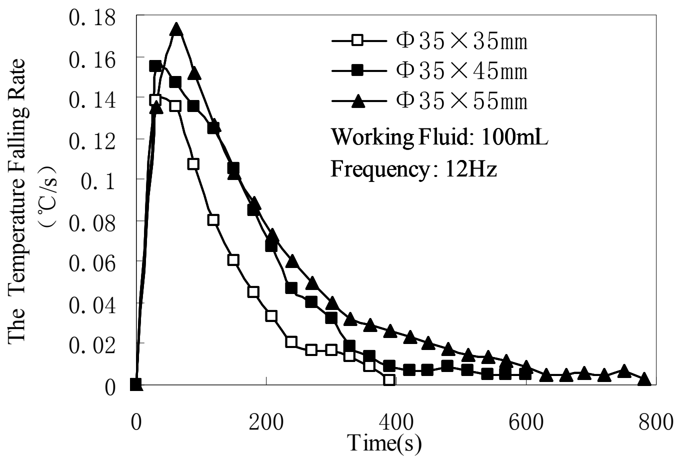

Piston
Displacer
(Regenerator)
Compression Space
Expansion Space
1
2
3
4
1
T_C
T_E
(a)
P
V
O
1
2
3
4
T_C
T_E
(b)

Fig. 2



25
20
15
10
5
0
−5
−10
−15
The Temperature of Cooler Head (℃)
Φ35×35mm
Φ35×45mm
Φ35×55mm
Ambient Temperature: 24℃
Frequency: 12Hz
0
200
400
600
800
Time(s)

Fig. 3



0. 18
0. 16
0. 14
0. 12
0. 1
0. 08
0. 06
0. 04
0. 02
0
The Temperature Falling Rate (℃/s)
Φ35×35mm
Φ35×45mm
Φ35×55mm
Working Fluid: 100mL
Frequency: 12Hz
0
200
400
600
800
Time(s)

Fig. 4

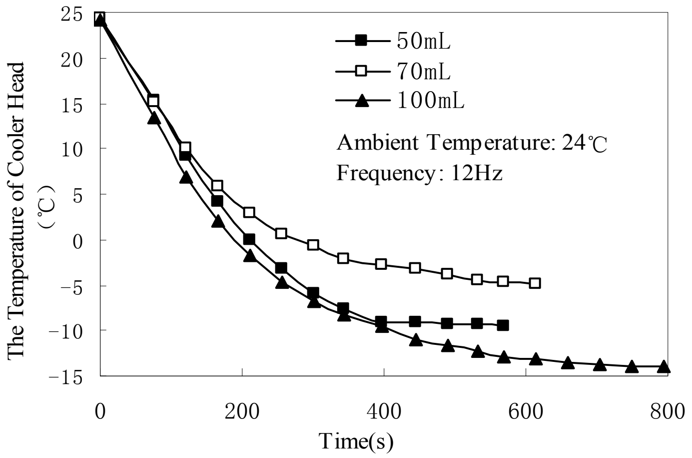
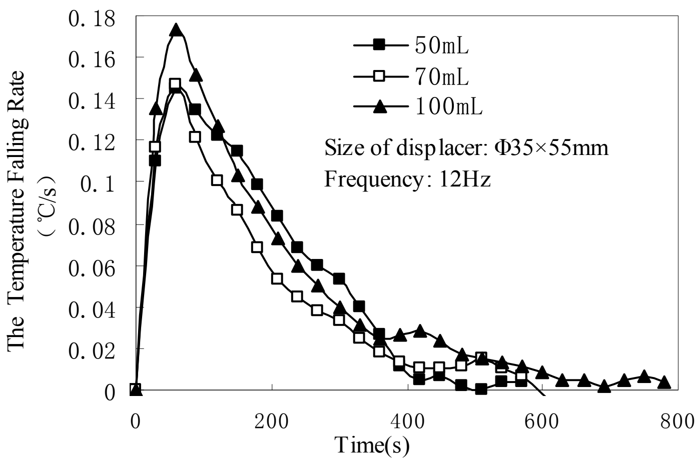

25
20
15
10
5
0
−5
−10
−15
The Temperature of Cooler Head (℃)
0
200
400
600
800
Time(s)
50mL
70mL
100mL
Ambient Temperature: 24℃
Frequency: 12Hz

Fig. 5



0. 18
0. 16
0. 14
0. 12
0. 1
0. 08
0. 06
0. 04
0. 02
0
The Temperature Falling Rate
(℃/s)
50mL
70mL
100mL
Size of displacer: Φ35×55mm
Frequency: 12Hz
0
200
400
600
800
Time(s)

Fig. 6

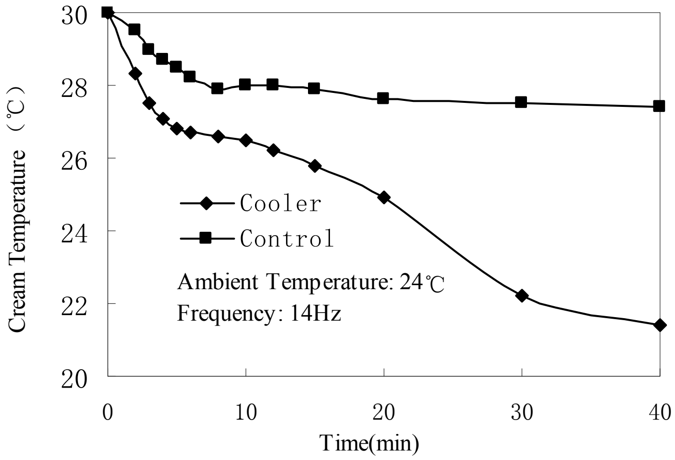
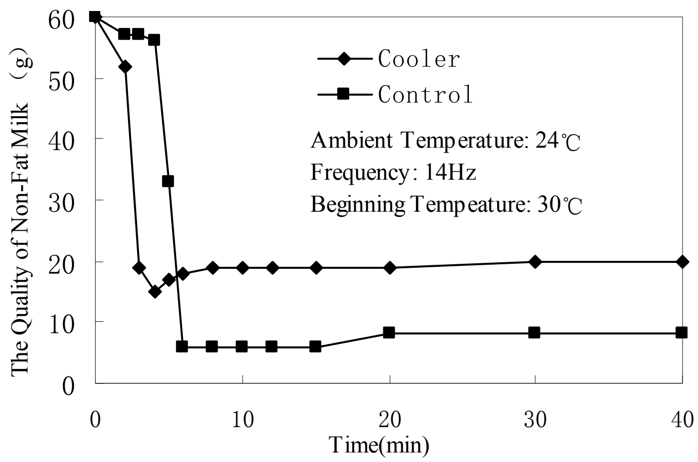

30
28
26
24
22
20
Cream Temperature （℃）
Cooler
Control
Ambient Temperature: 24℃
Frequency: 14Hz
0
10
20
30
40
Time(min)

Fig. 7



Cooler
Control
Ambient Temperature: 24℃
Frequency: 14Hz
Beginning Tempeature: 30℃
The Quality of Non-Fat Milk （g）
Time(min)
0
10
20
30
40
50
60
0
10
20
30
40

Table 1

Table 1 Content of Butter Component

Beginning temperature	Category	Content of water (%)	Content of fat (%)
From 10℃	Cooler	29.1	68.1
	Control	55.2	40.5
From 20℃	Cooler	28.7	68.3
	Control	48.0	47.2
From 30℃	Cooler	27.8	68.9
	Control	58.4	37.7