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Refrigeration supply of milk plants on base of automated water-cooling machines

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The objective of this paper is to study the effect of using the cold water as a storage source of refrigeration on the accumulator volume and power consumed during the process of milk cooling at the conditions of variable cooling load. This study has been based on various analyses of calculation results using a mathematical model. A comparison study is conducted between cold water and cold brine as a storage source of refrigeration for milk cooling process. A computer program was developed to simulate the appropriate equations that calculate the volume of accumulators and power required for water and brine system. The calculation method of cold accumulation system for milk plant has been given. The flow chart of the computer program has been represented. The results obtained show that the volume of accumulator is (58 m^3) for cold water and (59 m^3) for cold brine at the same conditions of maximum cooling load of milk about 206 kW, peak duration of 3,5 hours, water temperature difference of 2 °C, brine temperature difference of 2 °C, and operating period of refrigerating machine up to 17 hours a day. In addition to that it was found that the power required to operate the compressor of cold brine system is (90 %) greater than the power needed to operate the compressor of cold water system.

Key words: accumulation of energy, water as a storage source, simulation.

Introduction

Thermal storage can be used for applications where the peak load is confined to a limited number of hours in a day and the load for a few other working or operating hours is much less. In the balance time of 24 hours, there is no load whatsoever. Typical examples are process applications such as milk processing. In milk processing, the requirement of refrigeration is limited generally to six to eight hours a day [1], and there is no load during the balance period of 24 hours. Design a refrigeration machine at the conditions of maximum cooling load of milk (peak load) means that there will be need in large compressors, accordingly more power required for operating. To meat the peak load limited to a few hours, accumulation of cooling capacity in the form of cold water or cold brine is adopted. By this system, the refrigeration plant can work up to 17 hours a day. During the lean load periods and particularly in the zero — load hours, the refrigeration plant can be operated to generate thermal storage in the form of cold water or cold brine. The plant can also be operated during the period refrigeration is needed. This system thus reduces the size of the compressors as it is deigned for cooling load less than maximum cooling load of milk. As a result the power requirement of compressors is reduced. As mentioned above the brine is used as a storage source, but using the brine is conducted with corrosion of pipes and other parts of plant. In addition to that, the evaporators temperature necessarily has to be low about (−20 °C) for sub-cooling the brine using ammonia as a refrigerant [2]. Therefore the brine storage system will consume more power than the water storage system, where the evaporator temperature is not lower than (−5 °C) using R22 as a refrigerant. To prove that it is the case, the volume of cold water accumulator and, the volume of cold brine accumulator, the power consumed and capacity of refrigeration machine must be under consideration. It can be achieved either by experiments or by computer-based simulation. The latter saves time and money.

Theoretical part

This part is aimed to determine the power consumed and the energy saving ratio. For this purpose, the minimum volume of refrigeration accumulator required to meet the peak load limited to a few hours and the refrigeration capacity of machine needed to generate the accumulator during the lean load periods and particularly in the zero-load hours must be calculated. Consider a simplified schematic diagram of the plant shown in Fig. 1 where accumulator consists of well-insulated two-side tank, warm and cold.

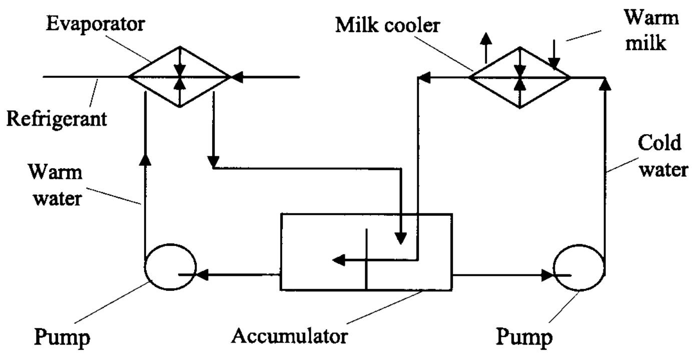

Fig. 1. Schematic diagram of the plant

The calculation method of water-storage system is expressed as follows: Refrigeration capacity is defined as [3]

$$Q_0 = \frac{((G_{wcp}\tau_{\max} + G_{wca}\tau_{\min})\, C_w \Delta t_{wc})}{(\tau_{\max} + \tau_{\min})}, \quad (1)$$

where $\tau_{\max}$ — is duration of the longest peak period;

$\tau_{\min}$ — is duration of the shortest lean load;

G_{wcp} — is the mass flow rate of water through milk cooler under peak load conditions defined as

$$G_{wcp} = \frac{Q_{mm}}{C_w \Delta t_{wc}}, \quad (2)$$

where Q_{mm} — is maximum load of milk;

C_w — is specific heat of water;

Δt_{wc} — is temperature difference of water at inlet and outlet of milk cooler;

G_{wcp} — is the mass flow rate of water through milk cooler for average load of milk in 24 hours determined as follows:

$$G_{wca} = \frac{Q_{ma}}{C_w \Delta t_{wc}}, \quad (3)$$

where Q_{ma} — is the average load of milk in 24 hours.

To find out the volume of accumulator, it is necessary to determine the mass flow rate of water through evaporator, which expressed as

$$G_{we} = \frac{Q_0}{W_c \Delta t_{we}}, \quad (4)$$

where Δt_{we} — is temperature difference of water at inlet and outlet of evaporator.

Once (G_{we}) is found then volume of accumulator (V_{ac}) is determined by the following equation [3]:

$$V_{ac} = \frac{(G_{wcp}\Delta t_{wc} - G_{we}\Delta t_{we})\, \tau_{\max}}{\rho_w\, (t_{\max} - t_{\min})}, \quad (5)$$

where ρ_w — is density of water;

$t_{\max}$ — maximum temperature of water in accumulator;

$t_{\min}$ — minimum temperature of water in accumulator.

As a result of peak load the temperature of water in accumulator is increased (accumulator discharge), to determine the temperature of water at any given duration of peak load, the following equation is used [3]:

$$t_{w1} = t_{\min} + \frac{(G_{wcp}\Delta t_{wc} - G_{we}\Delta t_{we})\, \tau_1}{\rho_w V_{ac}}, \quad (6)$$

where τ_1 — is the given duration of peak load restricted within the range of $(0 \leqslant \tau_1 \leqslant \tau_{\max})$.

On the other hand, the temperature of water in accumulator is decreased (accumulator charge) during the lean peak period in this case the following equation is used to find out the temperature of water during the charge period:

$$t_{w2} = t_{\max} + \frac{(G_{wca}\Delta t_{wc} - G_{we}\Delta t_{we})\, \tau_2}{\rho_w V_{ac}}, \quad (7)$$

where τ_2 — is the given duration of lean load restricted within the range of $0 \leqslant \tau_2 \leqslant \tau_{\min}$.

Equation (1) is used to determine Q_0.

Once that is found then duration of operating period of refrigerating machines is expressed by the following equation:

$$\tau_{w.m} = \frac{Q_{ma} \cdot 24 \cdot 60 \cdot 60}{Q_0 \cdot 60 \cdot 60}, \quad (8)$$

as well, the ratio of operating period a day is determined as

$$b_{w.m} = \frac{\tau_{w.m}}{24}. \quad (9)$$

Taken into account that the refrigerant used to cool the water being circulated through coils in the evaporator is R22, thus the refrigerating effect and work of compression per (kg) are determined at evaporator temperature of 268 K which is recommend by [4], and condensing temperature of 303 K.

Once refrigerating effect is determined, the mass flow rate of refrigerant is obtained as follows:

$$G_R = \frac{Q_0}{q_0} \quad (10)$$

thus theoretical power is calculated as

$$N_T = G_R W, \quad (11)$$

where W — is compression work per kg.

The energy conservation of water accumulation system is assessed by calculation the energy saving ratio as follows:

$$E_{CE} = \frac{N_{TM} - N_T}{N_{TM}}, \quad (12)$$

where N_{TM} — is theoretical power at the conditions of maximum load (peak load) of milk, which is determined as follows.

First, the mass flow rate of refrigerant is determined at the condition of (Q_{mm}) as

$$G_{RM} = \frac{Q_{mm}}{q_0}. \quad (13)$$

Thus,

$$N_{TM} = G_{RM} W. \tag{14}$$

To conduct a comparison between water-accumulation system and brine-accumulation system, the last is calculated for the same conditions of milk load and temperature difference in accumulator. This calculation is conducted using this calculation method, but in this time, the refrigerant is NH_3 as it is recommend [2] to cool the brine at evaporating temperature of 253 K.

Simulation method

To calculate the volume of accumulator, the refrigeration capacity, temperature of water in accumulator, theoretical power, and the energy saving ratio, a computer program is written. The flow chart of the computer program is shown in the following (Fig. 2).

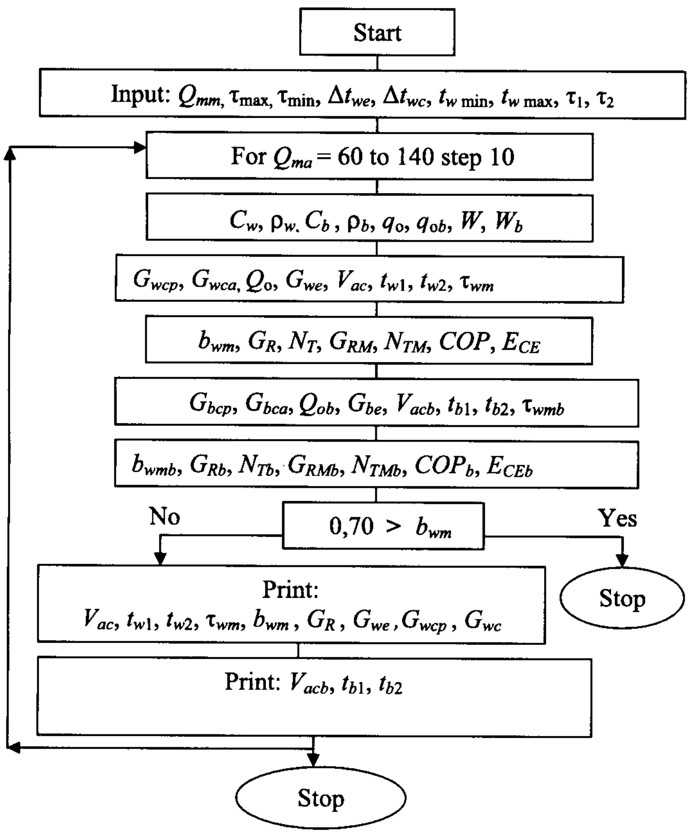

Fig. 2. Computer program

Results and discussion

In order to improve the cold water accumulation system and brine accumulation system for milk plant, the mathematical model can be used to study the effect of varying some of the design parameters. The results outlined below are based on (206 kW) maximum cooling load of milk, (2 °C) storage source (water or brine) temperature difference between the inlet and outlet of milk cooler. As well (2 °C) temperature variation of storage source in accumulator, (1 °C) minimum temperature and (3 °C) maximum temperature of storage source in accumulator, (2 °C) storage source temperature difference between the inlet and outlet of evaporator, R22 primary refrigerant for cold water accumulation system, NH_3 primary refrigerant for cold brine accumulation system.

Using the developed model and giving the average cooling load of milk (100 kW), the theoretical power required (NT) is calculated and illustrated with duration of peak load and cooling load ratio Q_{ma}/Q_{mm} (Fig. 3, 4) respectively. The energy saving ratio E_{CE} is calculated and shown with duration of peak load and duration of lean load (Fig. 5, 6) respectively. As well the energy saving ratio is illustrated with cooling load ratio Q_{ma}/Q_{mm} (Fig. 7). In addition to that, the changing in the storage source temperature in accumulator with time during the process of discharge and generation was under study and the obtained results are illustrated (Fig. 8). The effect of peak load duration on the accumulator volume is illustrated (Fig. 9).

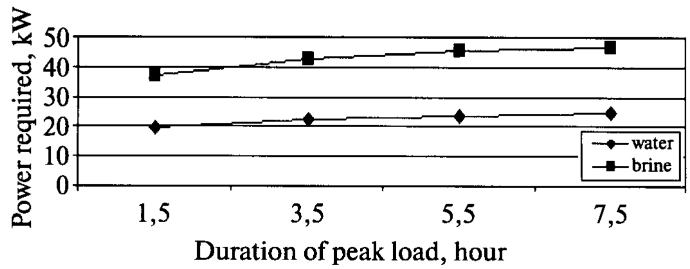

Fig. 3. Comparison of water system with brine system by theoretical power

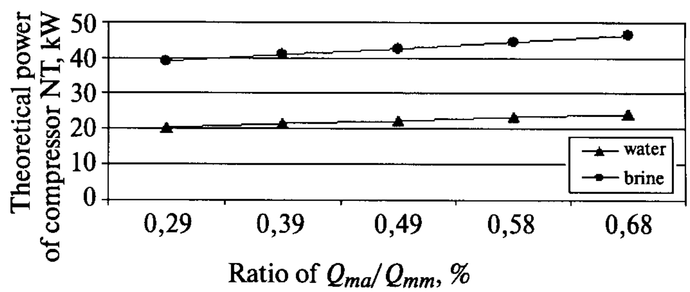

Fig. 4. Variation of theoretical power required with Q_{ma}/Q_{mm}

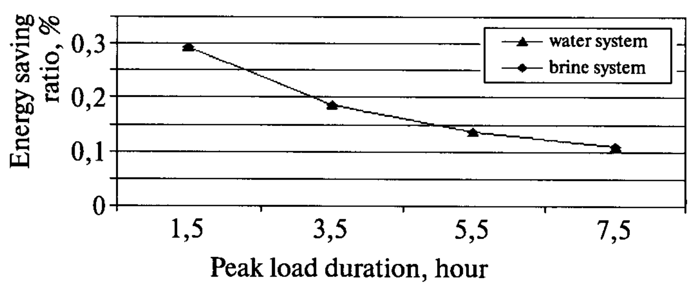

Fig. 5. The effect of peak load duration on the percentage of energy saving

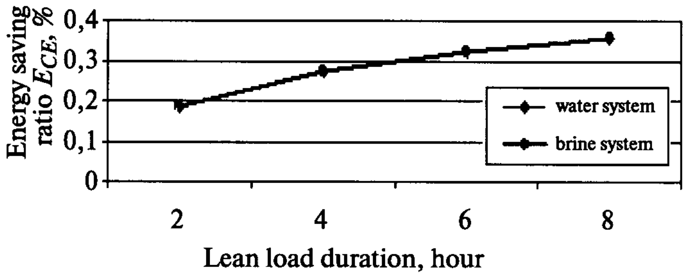

Fig. 6. The effect of lean load duration on the percentage of energy saving

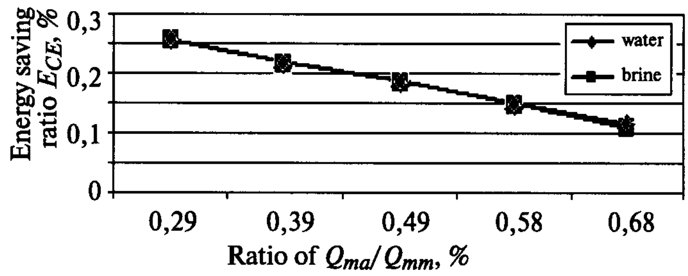

Fig. 7. The effect of milk load ratio Q_{ma}/Q_{mm} on the percentage of energy saving

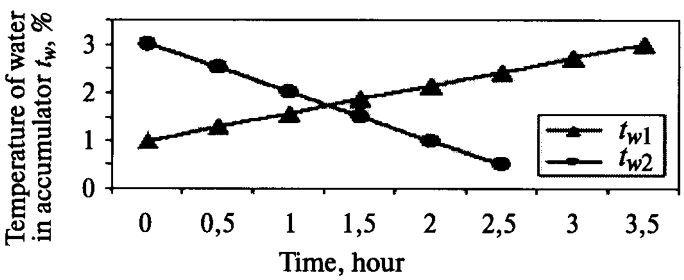

Fig. 8. Variation of water temperature in accumulator with time: t_{w1} — during discharge period; t_{w2} — during charge period

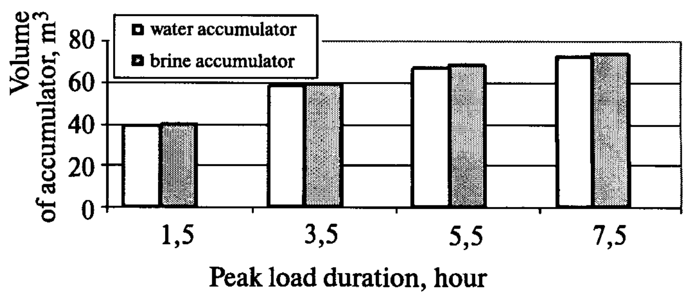

Fig. 9. Variation of accumulator volume with peak load duration

The results of this study demonstrate that using the cold water as a storage source in milk plant requires less power than brine. The theoretical power is reduced about 45 % as shown (in fig. 3, 4). The duration of peak load seems to have some influence on the power requirement and energy saving ratio (in fig. 3, 5). Increasing of peak load duration leads to an increasing in the power requirement and a drop in the energy saving efficiency. In addition to that a long duration of peak load calls for very large chilled storage source accumulators, as illustrated (in fig. 9). The reduction of the average cooling load of milk Q_{ma} according to the maximum load Q_{mm} is reflected in the less theoretical power of compressors and the higher energy saving percentage as demonstrated (in fig. 4, 7). The temperature variation in accumulator of 2 °C is indicated (in fig. 8). This variation of temperature is the same for the lean and peak load period. The consequence of this result is of significance as it indicates that the accumulator volume is successfully determined to meet the longest peak load, and refrigeration capacity is enough to generate the accumulator during the shortest lean load period. Fig. 6 indicates that the longer lean load period the greater energy saving percentage. This effect is a result of a small capacity of refrigeration machine required to generate the accumulator during the lean load period.

Conclusion

From the present study, the following conclusion can be drawn:

The power required for cold water accumulation system is substantially lower than that for the cold brine accumulation system. Such that a 45 % decrease in power required for operating the compressors is possible at any conditions of peak and lean load of milk. Comparing the energy saving ratio of cold water accumulation system and brine system with that of without accumulator shows that the energy saving ratio of (20–30) % is achieved within the short duration of peak load up to 4 hours, and lean load duration of (2–5) hours. In addition to that, to achieve this percentage of energy saving, the average cooling load of milk must be 50 % as minimum less than the cooling load of peak period. Another conclusion of this study is that the volume of accumulator for water refrigeration storage system equals the volume of accumulator for brine refrigeration storage system at any conditions of milk cooling load. The results of this study demonstrate that, a good computer model of the water accumulation system provides a useful tool for refining the design details and selecting the most appropriate design parameters for system operation and performance. The developed model and simulation method is flexible, hence the can be used as diagnostic tool to investigate the accumulation system of milk plants at any desired conditions.

Nomenclature

b — brine;

V_{acb} — volume of brine system accumulator;

Q_{ob} — refrigerating machine capacity of brine system;

t_{b1} — temperature of brine in accumulator during discharge process;

t_{b2} — temperature of brine in accumulator during generation process;

N_{Tb} — theoretical power of compressor in brine system;

E_{CEb} — energy saving ratio of brine system;

$COPb$ — coefficient of performance of brine system.

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