MILK PRODUCTION ENERGY USE FUNCTIONS FOR HERRINGBONE PARLORS

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ABSTRACT

The design of energy conservant or alternate energy systems for dairy farms requires the determination of milk production energy use. An analytical procedure was used to develop functions to estimate milk cooling and water heating energy use in herringbone parlors and a wide range of herd sizes. Verification with observed data for a particular case yielded very acceptable results.

1. Introduction

Historically, most forms of dairy farm fuels and energy sources have been relatively inexpensive. With cheap energy, accurate design and the need to determine the amount of energy used in milk production was not particularly important. However, higher energy prices have prompted a need for more efficient system designs and for the consideration of alternate sources of energy such as wind assisted or solar energy devices (Wiersma and Armstrong, 1979). As the number of dairy farms is decreasing and the average herd size is increasing, the energy cost per unit of milk produced has increased. Increased mechanization and higher sanitary standards required by law have all added to the increased energy use in dairy operations. The dairy industry has become increasingly electrical energy dependent.

To design an efficient energy-use system or to develop an alternative energy technology for an economic dairy farm management, a methodology for determining the energy used directly in milk production is required. Two of the major energy uses in dairy operations are milk cooling and water heating. It is estimated that water heating accounts for about 30 percent or more of the electrical energy consumed on the dairy farm while 25-45 percent is required for milk cooling (Frank, 1975). Evans (1975) reports that using booster coolers and water heating condensing units, improves energy efficiency ratio of the dairy system and conserves energy. The present study was conducted to develop the energy-use functions for milk cooling and water heating in dairy operations for herringbone parlors. Space heating in the dairy barn or milking parlor was not considered in this study. The study covered four energy-use systems or conservation levels:

1. Full energy conservation, both booster cooler and water heating condensing units are incorporated in the system,
2. partial energy conservation, booster cooler only incorporated in the system,
3. partial energy conservation, water heating condensing unit only is incorporated in the system, and
4. no energy conservation, system without booster cooler and water heating condensing unit.

Herringbone milking parlors were chosen for this study because analyses by Bickert and Armstrong (1976) and Wiersma and Armstrong (1979) indicate that this parlor type is more efficient than others in throughput and hot water use.

An analytical approach verified from actual records and observation was adopted in the study. The components of the system are given in Figure 1 which is one design for an energy conservant dairy management system. The warm milk from the milking parlor is passed through the tube precooler where it is cooled 5°C to 8°C, by tap water. It is stored in a bulk storage tank after it has been cooled to about 1°C to 3°C by chilled water from the refrigeration system. The tap water warmed 6°C to 10°C by the heat exchange process in the precooler may be used for drinking in wintertime and udder washing in the milking parlor, or could be passed through the condenser of the refrigeration unit for heating to a temperature of about 75°C. The hot water is required for washing and sanitization of milking units and for upkeep of sanitary conditions in the milking parlor. This study develops the functions which estimate the energy used in these processes and quantifies the savings obtained by having a precooler and water-heating condenser unit in the system.

2. Milk Cooling Energy Use

The development of milk production energy-use functions requires the determination of average milking time, the milk rate of flow in the system, and its relation to the milking parlor size. Milking time, (i.e., the time the milking machine is on the cow) and the actual production at each milking per cow was measured for 1,794 cows in 14 milking episodes at the Colorado State University dairy farm. The average milk production was 9.28 kg (20.45 lb) per cow per milking, which compared favorably with USDA (1978) official national average records of 9.09 kg (20.04 lb). The average milk flow rate was 1.47 liters (0.39 gal.) per minute per cow (see Table 1).

Milk leaves the cow's body at 33°C to 37°C and is stored in the bulk tank at 1°C to 3°C. Assuming average temperatures of 35°C and 2°C for the initial and storage temperatures of milk, respectively, a specific heat capacity of milk of 1.7662 kJ/K, a 365-day year, and using USDA milk production figures of 9.09 kg (20.04 lb) per cow per milking, the gross energy demand for milk cooling is given by:

$$Em = 239.78 \text{ kwh/cow-year} \qquad (1)$$

where Em = milk cooling energy demand without a precooler.

3. Milk Cooling Energy Use with a Precooler*

The extent of precooling is a function of the heat exchange coefficient of the precooler and the bulk flow rate of milk through the precooler. For a given design and size of the precooler and a selected constant water flow rate, the precooling will be a function of the bulk flow rate or:

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*A Surge hi-volume precooler is used because it was the only one for which data was available at the time of the study.

$$\Delta T = f(q)$$

where,

q = milk flow rate, and

ΔT = decrease in milk temperature in the precooler.

The milk flow rate, q, will depend on the number of cows milked simultaneously. In practice, dairy farm operators have all the stalls in the parlor filled at each milking episode. Therefore, if x is a parlor factor denoting the number of stalls on one side of the herringbone parlor, the capacity of the parlor and the number of cows milked at each episode will be $2x$, and x becomes an index of the size of the parlor. For example, a double-6 parlor denotes a herringbone parlor with 6 stalls on each side with a capacity of 12 cows per milking episode. Thus $q = f(2x)$ will relate the milk flow rate to the number of cows milked simultaneously, and also to the parlor size. From the milking episode record data in Table 1, the average milk flow rate computed was 1.474 liters per min-cow. Therefore, for any size milking parlor of capacity $2x$ lactating cows per episode, the milk flow rate is given by:

$$q = 2.95x \text{ liter/min} \tag{2}$$

where q and x are already defined.

The relation between parlor size and throughput is given in Table 2 (after Bickert and Armstrong, 1976). For an average level of mechanization comprising self-detaching milking units and crowd gate, and one milking operator, the following relation between throughput and parlor size was found to reproduce Table 2 behavior:

$$y = -16.08 + 44.49 \ln x \tag{3}$$

where y = throughput or cows milked per hour. An appropriate parlor size for a given herd size is selected based on throughput (allowing two milkings per day) with the constraint that,

$$K = \frac{n}{y} \leq 6.0 \tag{4}$$

where K = hours per milking episode, and n is the total number of cows to be milked, i.e., lactating herd size. The limit of six hours per milking allows for other parlor chores between milking episodes each day.

From manufacturer's specifications, Figure 2, the expected milk temperature drop for different flow rates with an assumed mean annual water temperature of 10°C was extracted and is summarized in Table 3. From Equation (2), the milk flow rate for the most common size of herringbone parlors is determined and the drop in milk temperature expected from these flow rates is extrapolated from Table 3. A power function was filled to this relationship given by:

$$\Delta T = 33.6\ q^{-0.40} \tag{5}$$

where ΔT = decrease in milk temperature through the precooler in degrees Celsius. The energy saved by the precooler E_s is then calculated and related to parlor size and is,

$$E_s = 155.91\ x^{-0.4} \text{ kwh/cow-year} \tag{6}$$

Combining Equations 1 and 6, the net energy demand for refrigerated milk cooling $E_{m_{net}}$ is then

$$E_{m_{net}} = 239.78 - 155.91\ x^{-0.4} \text{ kwh/cow-year}. \tag{7}$$

For a herd size, n, the energy use for milk cooling when a precooler is incorporated in the system is then given by:

$$E_{m_{net}} = n(239.28 - 155.91\ x^{-0.4})\ \text{kwh/year} \tag{8}$$

where $E_{m_{net}}$ = milk cooling energy use with precooler in the system.

4. Water Heating Energy Use

The total hot water use (at 75°C temperature) in a herringbone parlor was determined by Wiersma and Armstrong (1979), Figure 3. It is related to herd size by the power function

$$W = 43.63\ n^{-0.415}\ \text{liters/cow-day} \tag{9}$$

where W = dairy hot water use for herringbone parlors. The gross energy required to heat the water from 10°C to 75°C was derived and is given by

$$E_w = 1211.63\ n^{-0.415}\ \text{kwh/cow-year} \tag{10}$$

where E_w = gross water heating energy use. The energy exchange in the Surge precooler is almost 100 percent efficient. If all the hot water is derived from the preheated water, then,

$$E_{w_{net}} = 1211.63\ n^{0.585} - 155.91\ n\ x^{-0.40} \tag{11}$$

where $E_{w_{net}}$ = net water heating energy use for a given herd size, n, in kwh/year.

5. Net Water Heating and Milk Cooling Energy Use for the Four Levels of Energy Conservation

The four levels of energy conservation considered in the study depend on whether a precooler and water-heating condensing units, precooler alone, water heating condensing unit alone, or none of the units are installed in the system. Schematic representation of the Level 1 system incorporating the precooler and water-heating condensing units is given in Figure 1.

If the milk cooling system uses an ice builder with condensing units, then for each kilogram of water frozen, 334.94 kJ are recovered. In addition, heat is rejected by the condensing units. The heat removed from the water and that rejected by the condenser can be recovered in the form of usable hot water by using desuperheaters and water-heating condensing units. The temperature of the heated water depends on the system condensing temperature (Evans, 1977), and that of the refrigerant. Condensing units capable of recovering 100 percent of the total rejected heat can be obtained by careful sizing of the compressor and selection of an appropriate refrigerant. Kaman Sciences Corporation (1976) showed that by using Freon R-22 as a refrigerant and a suitable sized compressor, the heat rejected by the compressor and that removed from the milk is sufficient to meet the water heating energy demand. For Level 1 of energy conservation, therefore, the net energy demand for water heating and milk cooling will be equivalent to the milk cooling energy demand, and:

$$E_1 = E_{m_{net}} = n(239.28 - 155.91\ x^{-0.4})\ \text{kwh/year} \qquad (12)$$

where E_1 = dairy energy use for Level 1 energy conservation measures, kwh/year. For Level 2 system without condenser unit, the energy demand is the sum of Equations (8) and (11) and

$$E_2 = n(1211.63\ n^{-0.415} - 311.82\ x^{-0.4} + 239.28) \qquad (13)$$

where E_2 = dairy energy use for Level 2 system, kwh/year. For the Level 3 system, no precooler is used in the system, but the hot-water energy demand is met by proper sizing of the compressor. The milk production energy function at this level is thus,

$$E_3 = 239.28 \text{ n kwh/year} . \qquad (14)$$

For Level 4 system, no energy conservation measures are applied. Thus from Equations (10) and (14)

$$E_4 = 239.28 \text{ n} + 1211.63 \text{ n}^{0.585} \text{ kwh/year} \qquad (15)$$

where E_3 and E_4 are the dairy energy use for Levels 3 and 4, for a given herd size n, kwh/year.

6. Results, Verification of Functions and Conclusions

Equations (12), (13), (14), and (15) derived in this study are the milk production energy-use function for herringbone parlors. Equation (12) is for a system in which a specific precooler and adequately sized compressor with a water-heating condenser with appropriate refrigerant are incorporated. Equation (13) gives the energy use for a system in which a water-heating condenser is absent. Equation (14) is the function for a system in which a precooler is absent while Equation (15) is the energy-use function when neither a precooler nor water heating condensing unit is in the system. These functions have been used in computing the energy used in milk production for herd sizes of 50 to 500 and the results are given in Figure 4.

To verify the suitability of these functions, the milk cooling energy use in a system incorporating a precooler at Colorado State University was monitored for a 6-month period. Such a system falls into category of Level 2 by definition, and Equation (13) would estimate its milk production energy use. About 120 to 150 cows were milked daily at the Colorado State University dairy farm with an average milk production within 2 percent of USDA records. The actual energy used is compared with that predicted by the function in Table 5. There is a close agreement within 3 percent between the function and recorded data for a half-year period of observations.

The functions developed in this study provide a way of estimating milk production energy use. Figure 4 shows that a precooler and a water-heating condenser are effective energy savers in dairy milk production operations. When used together, they cut energy demands of milk production by about 50 percent. Many dairy farms use a refrigeration system which can be modified for condenser water heating at a minimal cost. A precooler at the time of the study cost about $1,250 (one thousand, two hundred and fifty dollars) installed. The cost of the unit could be recovered from energy savings in about a year, if the herd size is 100 or above and energy cost is 6¢/kwh or more. The incorporation of the precooler and water-heating condensing units is therefore recommended in dairy milking systems in such situations. The development of these milk production energy-use functions now provides a useful tool in more accurately designing alternate energy systems for dairy farms. The functions are used in the study of wind energy applications for dairy farms by the authors, the results of which are contained in the companion paper, "Dairy Farm Wind Energy Systems."

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Table 1. Measured milk production data at Colorado State University dairy farm

No. of Operations	No. of Cows Milked	Total Milk Production (kg)	Total Milking Time (min)	Average Milk Production Per Cow Per Milking (kg)	Average Milking Time Per Cow (min)	Milk Flow Rate (kg/min)
1	143	1,300.72	883.00	9.10	6.17	1.47
2	126	1,390.71	887.70	11.04	7.05	1.57
3	128	1,052.33	674.80	8.22	5.27	1.56
4	137	1,329.34	819.80	9.70	5.98	1.62
5	122	1,050.97	643.50	8.61	5.27	1.63
6	138	1,334.29	844.10	9.67	6.12	1.58
7	134	1,035.69	676.80	7.73	5.05	1.53
8	136	1,254.64	1,008.50	9.23	7.42	1.24
9	137	1,354.06	833.90	9.88	6.07	1.62
10	101	969.42	714.60	9.60	7.08	1.36
11	121	1,200.66	709.40	9.92	5.86	1.69
12	136	1,349.75	848.70	9.92	6.24	1.59
13	122	1,091.57	685.10	8.95	5.62	1.14
14	113	933.49	760.90	8.26	6.73	1.23
Total	1,794	16,647.66	10,990.80	129.84	85.95	--
Average	--	--	--	9.27	6.14	1.51

Table 2. Throughput for various herringbone parlor size (after Bickert and Armstrong, 1976).

Parlor Size	Double-4	Double-6	Double-8	Double-10
Throughput	45	64	78	85

Table 3. Drop in milk temperature through single Surge precooler.[1]

Milk Flow Rate (liters/min)	Milk Flow Rate (gal/min)	Milk Outlet Temperature °C	Drop in Milk Temperature °C
0	0	--	--
3.79	1	16.67	18.89
7.57	2	20.00	15.56
15.14	4	24.44	11.11
22.71	6	25.56	10.00
30.28	8	27.22	8.33
37.85	10	28.28	7.50
45.42	12	28.33	7.22

[1] Water inlet temperature assumed to be 10°C average.

Table 4. Drop in milk temperature through the precooler for different parlor sizes.

Parlor Size	Double-4	Double-6	Double-8	Double-10
Maximum milk flow rate,				
(Liters/min)	11.7711	17.6567	23.5419	29.4278
(gal/min)	(3.1096)	(4.6644)	(6.2191)	(7.7740)
Minimum drop in milk temperature, °C	12.4175	10.5443	9.3892	8.5811

Table 5. Comparison of observed milk production energy use for system incorporating a precooler (Level 2) at Colorado State University dairy farm, with function predictions.

Date	Power Meter Reading kwh	Period Covered (years)	Average Herd Size	Energy Use kwh
07:11:79	44236	--	--	--
01:11:80	54654	1/2	135	10418
Probable energy use for one calendar year			135	20836
Energy use as predicted by model - Equation (13) - for one year			135	20268.6

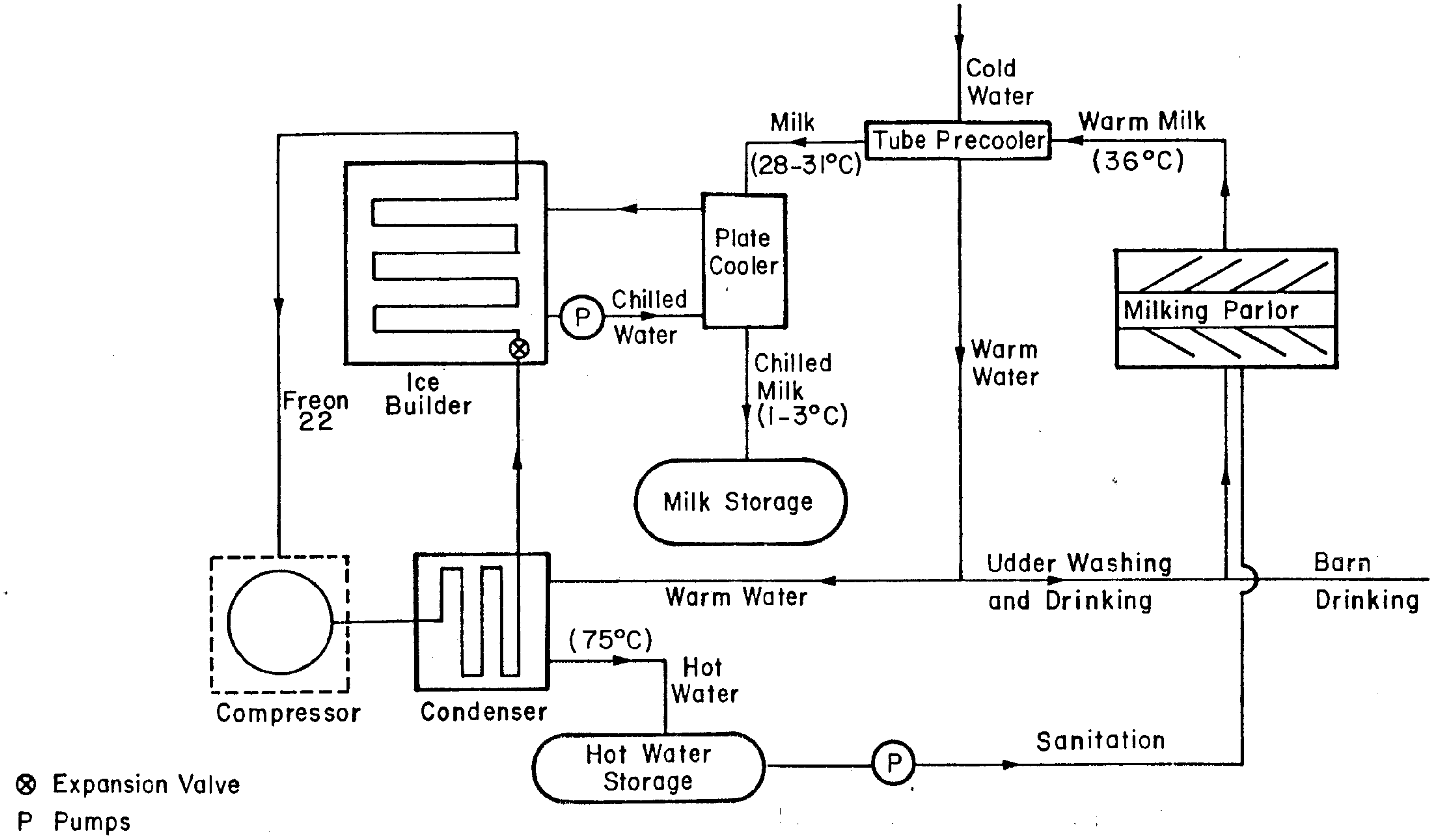

Figure 1. Components of an energy conservant (Level 1) milk production system.

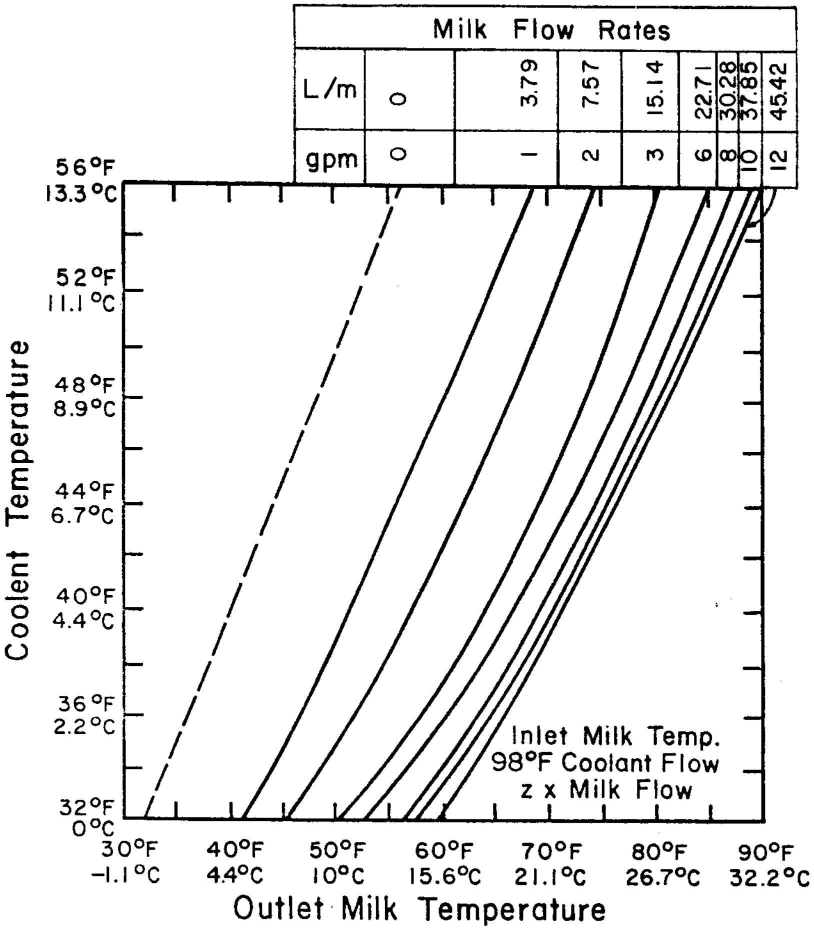

Figure 2. Relation between milk flow rates and outlet milk temperature for Surge precooler (Surge manufacturer's specifications for Model No. 80463).

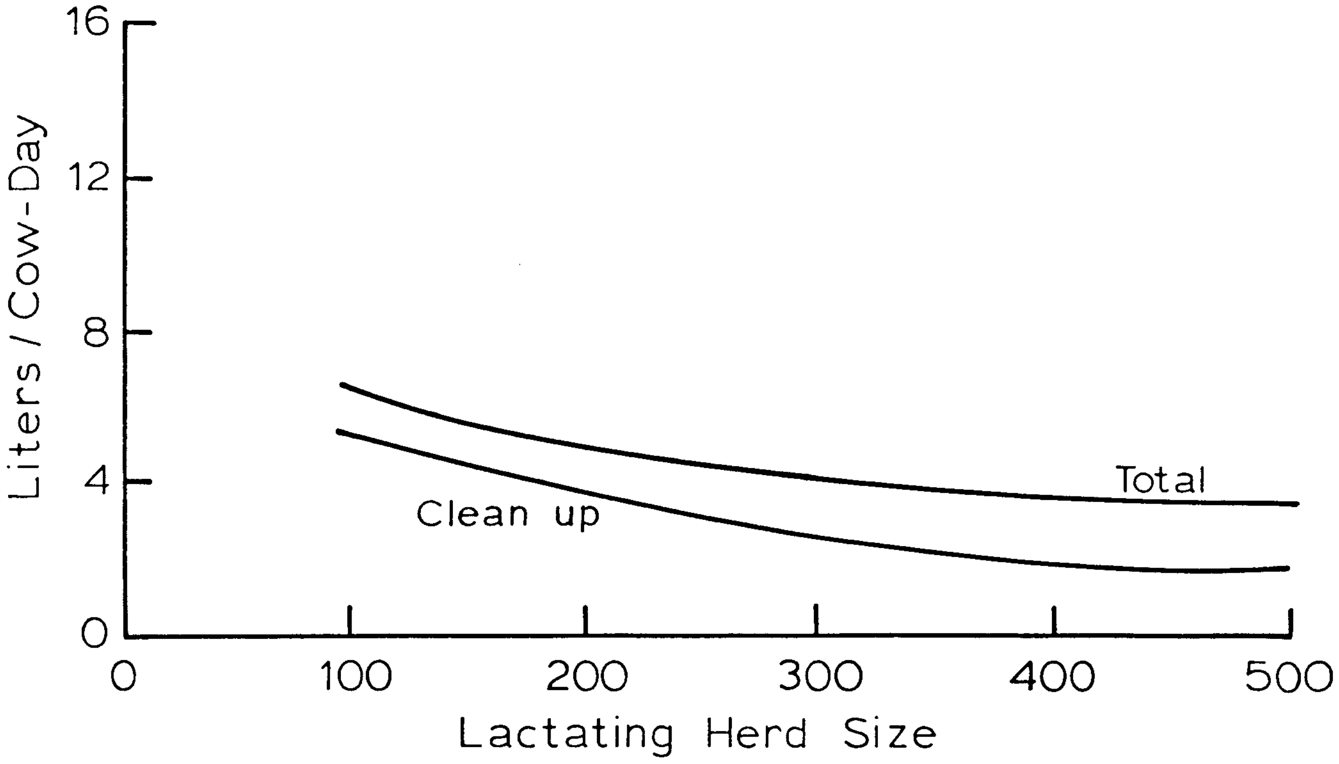

Figure 3. Hot-water use (75°C temperature) for herringbone parlors (Wiersma and Armstrong, 1979).

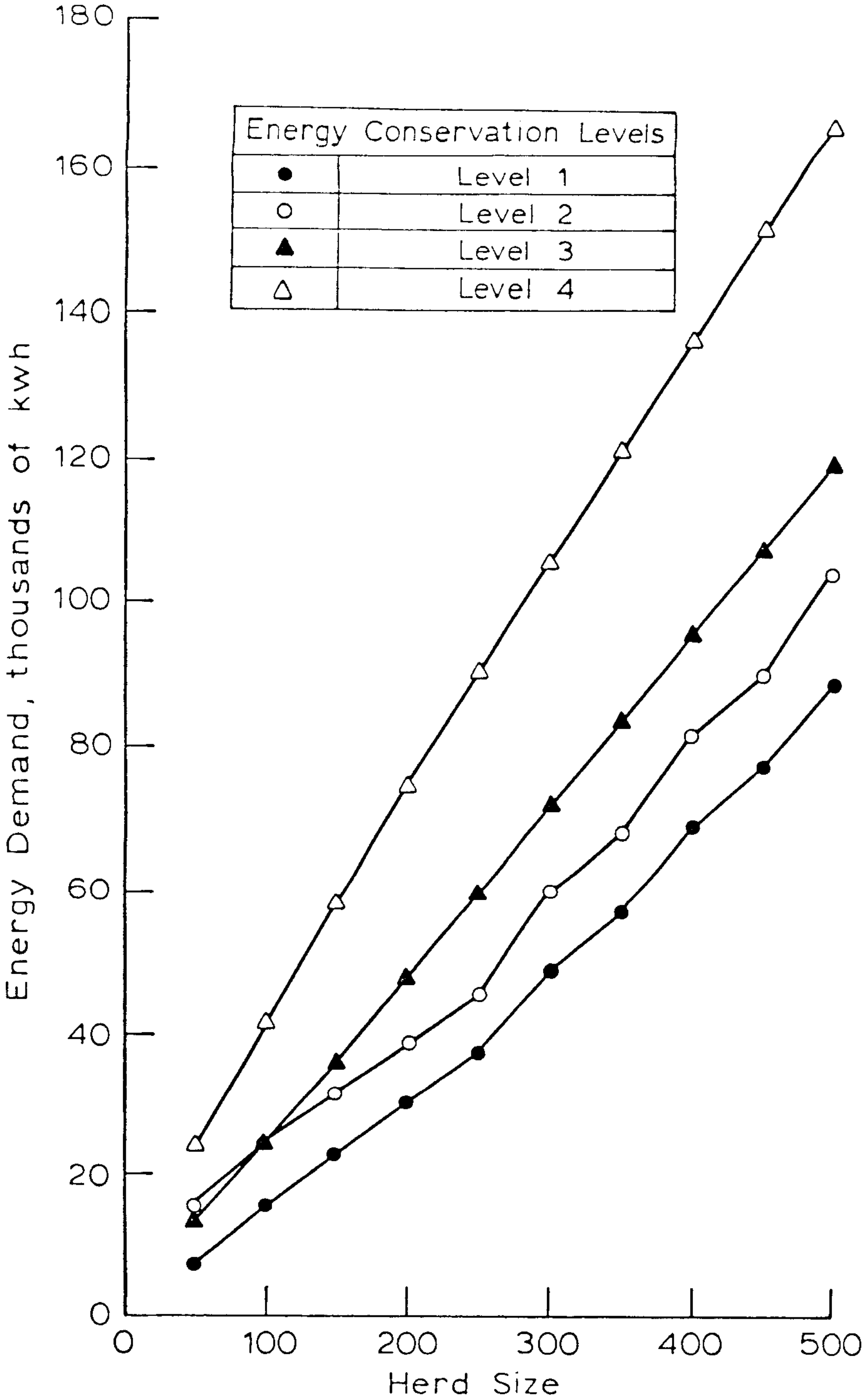

Figure 4. Annual milk-cooling and water-heating energy use versus lactating herd size for four energy conservation levels.

LIST OF FIGURES