USING ICE SLURRY AS SECONDARY REFRIGERANT FOR CHARGE REDUCTION IN INDUSTRIAL FACILITIES

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ABSTRACT

This work analyses warming impact and electricity cost in farm milk cooling facilities when direct expansion systems are replaced by ice slurry based secondary refrigeration systems. The environmental improvement obtained has been assessed by comparing the TEWI values obtained using ice slurry with those obtained using a direct refrigeration facility. Economical effects have also been assessed by evaluating power consumption and taking into account the feasibility of benefiting from reduced electricity rate by producing and accumulating ice slurry during off-peak hours.

KEYWORDS

Ice slurry; TEWI; Charge reduction; Milk cooling tank.

1. INTRODUCTION

Charge reduction in refrigeration systems is probably the most feasible solution to the environmental problems derived from the use of HFC-refrigerants (greenhouse effect) as well as the local danger problems derived from the use of “old” natural alternative refrigerants such as ammonia (toxicity) and hydrocarbons (flammability). This charge reduction can be achieved both at the system and the components level. It is shown that the use of secondary refrigerants in indirect refrigeration systems may result in substantial reduction of primary refrigerant charge. Nevertheless, the use of secondary refrigerants usually involves a decrease in the system performance mainly related to the additional heat exchanger needed between the refrigerant and the secondary fluid as well as the power consumption of pumps and other auxiliary equipment.

Most of the disadvantages of the secondary refrigerants come from their low specific heat capacity compared to primary refrigerants. This leads to an increase in the refrigerant mass flow rate and the size of the heat exchangers for a given heat exchange duty. Ice slurry is a secondary phase change refrigerant which, thanks to the latent heat of the ice crystals, has a much higher specific heat than usually used single phase secondary refrigerants. In this way, the use of ice slurry as secondary refrigerant potentially allows reducing the disadvantages related to the indirect refrigeration systems. An additional advantage of ice slurry is the possibility of cold thermal storage. Thanks to the high specific heat capacity of ice slurry, great thermal capacities can be achieved with relatively low volume requirement.

Based on the theoretical analysis of heat exchangers behaviour presented in previous works, this paper studies charge reduction in three different size indirect refrigeration facilities working with ice slurry. The environmental improvement obtained has been assessed by comparing the TEWI values (Total Equivalent Warming Impact) obtained using ice slurry with those obtained using a direct refrigeration facility. Economical effects have also been assessed by evaluating power consumption and taking into account the feasibility of benefiting from reduced electricity rate by producing and accumulating ice slurry during off-peak hours.

2. ICE SLURRY PRODUCTION & APPLICATION

In order to produce ice slurry, two different mechanism of ice crystal nucleation can be used: heterogeneous or homogeneous nucleation (Kauffeld et al, 2005). Several different technical solutions are currently available to produce ice slurry, although only a few of them are already applied commercially. Nowadays, the scraped surface ice slurry generator is the most technologically developed and widely accepted ice slurry generation process. Systems with mechanical scrapers produce ice slurry based on a heterogeneous nucleation process, although the ice generation mechanisms in this type of generators is not yet well known (Stamatiou et al, 2005). Less establishes than scraped surface systems, ice slurry systems using the supercooled water method have been developed and introduced into air conditioning systems by several companies in Japan (Tanino et al, 2005); this systems produce ice slurry based on a homogeneous nucleation process. Many other techniques exist to produce ice slurry, although most of them are now in development.

Independent of the technique used to produce ice slurry, the efficiency of the cooling system decreases compared to direct expansion systems and even to single phase secondary systems. Nevertheless, thanks to the high thermal capacity of ice slurry, in most cases the ice production systems are combined with storage systems, resulting in smaller refrigeration systems and operational savings where off peak tariff are available. Moreover, thanks to its low temperature and high thermal capacity, the use of ice slurry as secondary refrigerant can lead to important savings in energy consumption in the secondary distribution loop.

The way how ice slurry is applied depends on the specific use. Typically it can be distinguished between:

- Direct contact ice slurry application. The most typical example are ice slurry fish cooling systems; in this facilities the ice slurry is directly applied over the fish, which is totally covered by the slurry.
- Direct ice slurry application. Most of ice slurry facilities work in this way; in this case, ice slurry flows from the storage tank directly to a heat exchanger where ice slurry exchanges heat with another fluid (including air in fin and tube heat exchangers).
- Direct carrier fluid application. In order to avoid the problems attached to ice slurry application (typically the blockage of the small flow passages in some high efficiency heat exchangers), in some applications ice slurry is used as a thermal storage media, but only its liquid phase is pumped towards the thermal loads.
- Indirect ice slurry application. In some applications, an additional secondary refrigerant exists which transport the energy between the ice slurry and the final load. In these cases, ice slurry application can be considered as an indirect application. The most typical examples are ice slurry based air conditioning systems, which usually employs a chilled water circuit in order to transfer the heat from the air to the ice slurry.

Over the last few years, many ice slurry plants have been used in different applications as reported by Bellas and Tassou (2005). The most important are comfort cooling, commercial refrigeration (mainly retail food applications) and industrial processes (mainly fish processing plants although ice slurry had also been used in other types of food processing plants or in mining industry).

3. CASE STUDY: MILK COOLING SYSTEM

Although refrigerant charge reduction feasibility is one of the advantages most usually associated of the use of ice slurry, only research work regarding retail food applications have focused their attention on this aspect, and even in these cases, charge reduction results have not been reported in most research papers. In fact, most of the ice slurry generators (ISG) commercially available are flooded type evaporators, with high values of specific refrigerant charge (defined as refrigerant mass per unit refrigerant capacity). Depending on the specific application, the refrigerant charge obtained using this type of ISGs in substitution of direct expansion systems can be in some cases greater than those corresponding to the original system.

This work analyzes energy consumption, charge reduction and warming impact when ice slurry based cooling systems are used to replace direct expansion milk cooling systems. The most suitable tools for calculate the warming impact of a refrigerant facility are the TEWI, which is a combined measure of the direct chemical greenhouse gases (GHG) emission effect with the indirect energy related CO_2 emissions of the systems in which they are used (Fischer et al, 1991) and the LCCP (Life Cycle Climate Performance), which adds to the TEWI the direct GHG emissions during manufacture and the indirect GHG emissions associated to energy consumption during the production of substances. Nevertheless, according to Campbell and McCulloch (1998), the implications for climate change of the production of HFCs are insignificant in comparison with other stages of the life cycle of a refrigerator and have no role in the TEWI. There exist other methods like TWPA (Total Warming Prediction Analysis) or CWP (Composite Warming Potential) for assessment of time variation of global warming effects (Sekiya, 2007) but these methods are not as widely accepted as TEWI or LCCP. Taking into account all the previous considerations, TEWI calculation has been finally adopted as the method to evaluate the environmental impact for both the direct expansion and the ice slurry based milk cooling systems.

Direct expansion systems are the most common choice in farm milk cooling systems. In these systems, the evaporator plates are incorporated in the lower portion of the storage tank, in direct contact with the milk. Milk cooling takes place within the tank and one or more agitators move the milk over the evaporator plates for cooling. The refrigerated surface area is limited by the tank geometry and therefore, in many cases, the ability to remove heat from the milk fast enough to meet cooling requirements with high milk loading rates is not possible without reducing evaporator surface temperature to the point where freezing of milk may occur. Agitating warm milk for long periods of time can also be detrimental to milk quality. The milk cooling tank is usually not completely filled at once. A two milking tank is designed to cool 50 % of its capacity at once, a four milking tank is designed to cool 25 % of its capacity at once, etc. Therefore, the cooling performance depends on the number of milking it takes to completely fill the tank, the ambient temperature and the cooling time. In Europe, the EN standard 13732 sets different classes of cooling performance based on these three parameters (number of milkings, ambient temperatures and cooling times) as summarized in Table 1. Similar classifications are given by the international standard ISO 5708 or the American standard 3A 13-10.

Table 1. Cooling performance for bulk milk coolers on farms (EN 13732 Standard)

1. Number of milkings class				
2	2-milking tank designed to cool 50 % of its capacity at once			
4	4-milking tank designed to cool 25 % of its capacity at once			
6	6-milking tank designed to cool 16.7 % of its capacity at once			
2. Ambient temperatures class				
Class	A	B		C
Performance Temperature (PT)	38 °C	32 °C		25 °C
Safe Operating Temperature (SOT)	43 °C	38 °C		32 °C
3. Cooling time class (maximum cooling time to cool any milking from 35 °C to 4 °C)				
Class	O	I	II	III
Time	2 hours	2.5 hours	3 hours	3.5 hours

The milk cooling tanks analyzed in this work are assumed to be class 2 B II (milking tank designed to cool 50 % of its capacity from 35 ºC to 4 ºC in 3 hours at an ambient temperature of 32 ºC). Three different tank capacities of 1.5, 5 and 9 m^3 were studied. Both specific heat and density of milk are influenced by its fat content and temperature. Since the milk directly comes from the cow milking machine, it can be considered whole milk (3.5 % fat). For a temperature range between 4 and 35ºC, the specific heat c_p of whole milk can be considered constant and equal to 3890 $kJ\cdot kg^{-1}\cdot K^{-1}$, whereas its density ρ_m is around 1032 $kg\cdot m^{-3}$.Therefore, the cooling capacity $\dot{q}$ required to cool a n-milkings tank of volume V from 35 ºC to 4 ºC in 3 hours can be obtained as:

$$\dot{q} = \frac{\rho_m V c_p \Delta T}{n\cdot\Delta t} = \frac{1032\cdot V\cdot 3890\cdot(35-4)}{n\cdot 3\cdot 3600} = 11523\cdot V/n\,(W) \tag{1}$$

Usually milk cooling tanks had its own condensing unit, which only produces the refrigeration effect required to cool the milk stored in one tank. The cooling capacity of any condensing unit depends on tank volume and class and it must be at least equal to (and normally higher than) the value obtained applying equation (1). In this work it had been assumed that this cooling capacity is strictly equal to the minimum capacity required obtained by applying equation (1). The refrigerant charge depends both on the condensing unit and the evaporator characteristics. Since there are many different condensing units and bulk tanks available in the market, is not easy to predict the refrigerant charge. The values finally adopted is this work had been taken from a brochure of Kool Way® scroll condensing units designed to provide cooling for Kool Way® milk tanks. These values show a good agreement with typical refrigerant charge values obtained from bibliography (Poggi et al, 2008; Suwono, 2008). Table 2 summarizes the main characteristics of the cooling tanks (condensing units included) analyzed in this work.

Table 2. Studied bulk tanks & condensing units features.

Model	Volume	Class	Cooling capacity	Refrigerant charge	Energy consumption
1500L	1.5 m^3	2 B II	8.64 kW	8.16 kg	4.39 kW
5000L	5 m^3	2 B II	28.79 kW	19.94 kg	14.64 kW
9000L	9 m^3	2 B II	51.82 kW	29.91 kg	26.35 kW

Since evaporation temperature and superheat value depend on the milk temperature, variable operating conditions had been taken into account in order to obtain the condensing unit performance when cooling milk from 35 to 4 ºC. Assuming a 25 ºC ambient temperature and air cooled condenser, Bitzer software version 5.1.2© had been used to obtain the performance of Bitzer condensing units suitable for the bulk tanks analyzed. Performance had been obtained varying evaporation temperatures and superheat values according to the values provided in the Kool Way® scroll condensing unit brochure.

4. ICE SLURRY BASED ALTERNATIVE COOLING SYSTEM

In order to reduce the warming impact of the milk cooling facility, an ice slurry based alternative indirect cooling system has been analyzed. Usually the energy consumption in an ice slurry based refrigeration system is higher than in an equivalent direct expansion system. Given that the main objective is to reduce the TEWI, is absolutely essential to reduce the total refrigerant charge. Nowadays the ISGs more commercially successful are the ModuPak® Deepchill® (from Sunwell Technologies Inc.) and the ORE® (from Paul Mueller Company). As cited in the first paragraph of section 3, both of them are flooded type evaporators, with high values of specific refrigerant charge and therefore could not be used in order to reduce the TEWI. Many other manufacturers of ISGs exist and some of them assure that their systems allow to reduce the refrigerant charge but, among all the manufacturers analyzed by the authors, only Crytec® provides technical information enough to establish a comparison between direct and indirect milk cooling. Table 3 summarizes the main features of the Crytec Bubble Slurry™ systems used in the comparison presented in this work. These systems produce ice slurry by a homogeneous nucleation process, based on the subcooling effect combined with the injection of a certain amount of air into the cooling medium (the liquid that will transform to ice slurry) and the rubbing effect provided by two rotating wipers which prevent ice crystallization on the cooled surface of the crystallizer, and move the crystallization process to the center of the cooling medium.

Working continuously 24 hours a day, model CR-004 will be able to produce the cooling effect required by 5 1500L model bulk tanks, whereas model CR-010 will be able to serve to 5 5000L model bulk tanks and model CR-020 will be able to serve to 5 9000L model bulk tanks. Alternatively, assuming that ISG works only during the off-peak period of electricity demand, the number of bulk tanks served by each generator is reduced to 3 (the electric rate structure varies from country to country; current Spanish domestic tariff applied to residential customer has been used in the comparisons presented in this work).

Table 3. Ice slurry generators features.

Model	Cooling capacity	Rated power	Refrigerant type	Refrigerant load
CR-004	13.5 kW	8.9 kW	R 507	12 kg
CR-010	40 kW	25.4 kW		18 kg
CR-020	70 kW	44.4 kW		25 kg

Figure 1 shows a schematic representation of the 2 different configurations analyzed. Configuration (a) corresponds to 14 hours/day service of the ISG and configuration (b) corresponds to a 24 hours/day service. The process is the same for both configurations. During the off-peak period of electricity demand (a) or during the whole day (b), the ISG (1) produces ice slurry which is stored in the storage tank (2). Twice daily the milk comes from the milking facility at 35ºC and pass through the corrugated tube heat exchanger (3) where it is cooled down to 4 ºC by the ice slurry coming from storage in a counter-flow arrangement. Finally, the cooled milk flows into the milk storage tank (4). Once daily the milk is transported to the dairy plant, the tanks are cleaned and the process starts again.

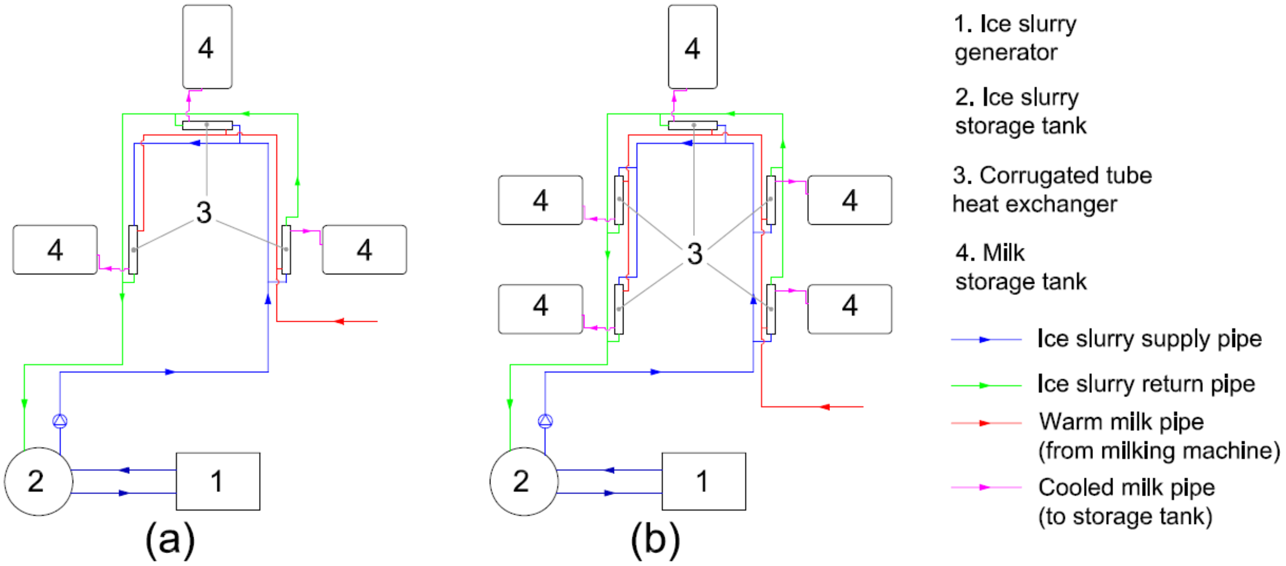


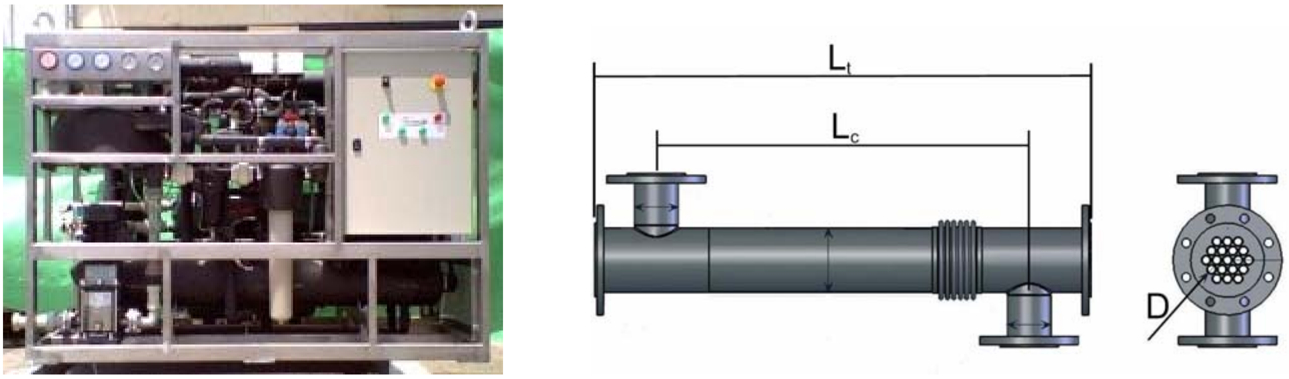
Figure 1. Ice slurry based milk cooling facilities analyzed. Ice slurry generator working 14 hours/day (a) and 24 hours/day (b).

Three different sizes had been analyzed for each configuration. In the small (S) size, a CR-004 model ISG produces the cooling effect needed to serve 3 (a) or 5 (b) 1500L model bulk tanks; in the medium (M) size, a CR-010 model ISG serves to 3 (a) or 5 (b) 5000L model bulk tanks; finally, in the large (L) size, a CR-020 model ISG serves to 3 (a) or 5 (b) 9000L model bulk tanks. Three different sizes corrugated tube heat exchangers had also been used. They are K Series heat exchangers by the HRS-Spiratube Company. They are all welded stainless steel multitube heat exchanger with the inner tubes corrugated, designed for use in industrial applications. Its main features are summarized in Table 4. Figure 2 shows a photograph of the Crytec Bubble Slurry^{TM} CR-010 model (a) and a sketch of the HRS-Spiratube K Series heat exchanger (b).

Table 4. Features of the three different heat exchangers used.

Heat exchanger reference	**Number of tubes**	**D**	**L_t**	**L_c**
K13-6.0.304/316LH	13	18 mm	5.91 m	5.694 m
K37-6.0.304/316LH	37	18 mm	5.91 m	5.648 m
K55-6.0.304/316LH	55	18 mm	5.91 m	5.6009 m

Thanks to its high thermal capacity, when ice slurry is used as secondary refrigerant, multiple heat exchangers can be serially connected without introducing a significant reduction in the temperature difference in the downstream equipment. In these conditions, a mono pipe system can be used. Nevertheless, in the case analyzed in this work, the ice slurry mass flow rate necessary to obtain a milk outlet temperature of 4 ºC in each heat exchanger is so high that the pressure drop in each heat exchanger is three times the value obtained in an equivalent dual pipe system. Consequently, the configuration finally adopted is a dual pipe system as represented in Figure 1.



(a) (b)

Figure 2. Crytec Bubble Slurry^{TM} CR-010 model (a). Sketch of the heat exchanger used (b).

5. RESULTS AND DISCUSSION

In order to obtain the warming impact of both, the direct expansion and the ice slurry based cooling systems is necessary to calculate their energy consumption. According to standard EN 13732, tank insulation must be able to avoid temperature increases higher than 3 ºC in 12 hours for the performance temperature. In most cases and depending on tank capacity, tank manufacturers assure lower temperature rise rates. For this reason, energy consumption necessary to maintain milk temperature at 4 ºC had been neglected for both the direct expansion and the ice slurry based systems. To obtain the energy consumption of the direct expansion system values for the condensing unit reported in Table 2 had been considered. These values include compressor and condenser fans power consumption.

Energy consumption in ice slurry based system is more complex to obtain because three different energy demands must be taken into account:

- Ice slurry generator: its energy consumption values are provided by the manufacturer and summarized in Table 3. Those values include refrigerant and air compressor, process pump and evaporator wiper motor, but do not include condenser fans demand. Fans demand had been assumed to be a 5 % of the rated power values provided in Table 3.
- Ice slurry storage system: using a homogeneous storage system, the probability of an unsafe operation decreases but, on the other hand, the energy demand of the mixing system increases total energy consumption. According to Hansen et al (2002) the specific power consumption of the mixer is around 70 W per m^3 storage volume. The required mixing power rises significantly above 30 wt-% ice fraction and hence, storage volume had been calculated assuming 30 wt-% ice fraction. Meili et al (2001) have shown that an intermittent operation of mixing allows important energy savings, turning the mixer off during no demand periods. According to their recommendations, energy consumption for the mixing system had been calculated assuming 7 hours of daily work.
- Ice slurry pumping system: twice daily the milk flows through a corrugated tube heat exchanger where is cooled down by the ice slurry. Pumping power depends on ice slurry mass flow rate, heat exchangers features and total circuit length. In order to optimize the ratio between heat transferred and pumping power, ice slurry mass flow rate in each corrugated tube is fixed in 375 kg/h (Illán and Viedma, 2009). Features of the three different heat exchanger used are summarized in Table 4 and the total circuit length had been assumed to be proportional to the facility size. Pumping power has been calculated simultaneously to heat transfer rate using the correlations proposed by the authors for Nusselt number and Darcy friction factor for ice slurry flow through horizontal smooth and corrugated pipes (Illán and Viedma, 2008a, 2008b).

The contribution to global warming (TEWI) of the refrigerant systems analyzed has to be evaluated taken into account both the energy consumption and the refrigerant emissions:

$$TEWI = M \cdot GWP \cdot \left[l \cdot n + (1 - a) \right] + nEb \tag{2}$$

with:

- M: nominal charge of refrigerant in the system (kg).

- *GWP*: global warming potential (kg eq. CO_2).
- *l*: leakage rate (kg of leakage/ initial charge).
- *n:* operation life of the system (years).
- *a:* recovery rate (kg of recovered refrigerant/ initial charge).
- *E:* annual energy consumption (kWh/year).
- *b:* CO_2 emissions per electric kWh of produced power (kg CO_2/kWh).

Once calculated the energy consumption *E* for each refrigeration system, the CO_2 content of one kWh is dependent on the energy mix in power generation. The power energy mix in 2007 in Spain gave an average CO_2 emission factor *b* of 0.4 kg CO_2/kWh (MITYC, 2008), which has been used in this work to obtain indirect emissions.

In order to develop direct emission calculations, a operation life *n* of 15 years, a leakage rate *l* of 15 % and a recovery rate *a* of 70 % had been considered for both, direct expansion and ice slurry based systems. *GWP* depends on the refrigerant used (R507A for ice slurry based system and R404A for direct expansion system) and nominal charges of refrigerant *M* are provided in Tables 2 and 3 for each refrigeration system. Results of the TEWI calculations for the six refrigeration systems analyzed are given in Table 5. According to these results, the replacement of direct expansion systems by ice slurry based secondary refrigeration systems allows to decrease the refrigerant charge and the warming impact in all the cases analyzed.

Table 5. TEWI calculations (15 years analysis).

		DIRECT EXPANSION SYSTEM			ICE SLURRY BASED SYSTEM											% Decrease in TEWI
	System size	Ref. charge	Daily energy consumption	TEWI	ISG model	ISG power	Ref. charge	Heat exhanger	Circuit length	Pipe DN	Pumping power	Storage tank	Mixing power	Daily energy consumption	TEWI	
3 milking tanks	S	3×8.16 kg	79.05 kWh	364418	CR-004	8.9 kW	12 kg	K13 6.0	50 m	50	0.7 kW	7 m^3	0.63 kW	129.68 kWh	360790	0.9956
	M	3×19.94 kg	263.52 kWh	1063792	CR-010	25.4 kW	18 kg	K37 6.0	62.5 m	75	1.16 kW	17 m^3	1.19 kW	364.7 kWh	998425	6.1447
	L	3×29.91 kg	474.33 kWh	1790460	CR-020	44.4 kW	25 kg	K55 6.0	78 m	110	0.98 kW	31 m^3	2.17 kW	637.39 kWh	1742654	2.6700
5 milking tanks	S	5×8.16 kg	131.76 kWh	607364	CR-004	8.9 kW	12 kg	K13 6.0	50 m	75	0.98 kW	12 m^3	0.84 kW	220.43 kWh	541855	10.7858
	M	5×19.94 kg	439.2 kWh	1772987	CR-010	25.4 kW	18 kg	K37 6.0	62.5 m	110	0.77 kW	29 m^3	2.03 kW	624.33 kWh	1579751	10.8989
	L	5×29.91 kg	790.55 kWh	2984099	CR-020	44.4 kW	25 kg	K55 6.0	78 m	140	0.6 kW	52 m^3	3.64 kW	1091.45 kWh	2787765	6.5793

Table 6. Electricity cost analysis.

		DIRECT EXPANSION SYSTEM		ICE SLURRY BASED SYSTEM	SAVINGS					
	System size	Annual energy costs (A)	Annual energy costs (B)	Annual energy costs (IS)	Annual savings (A-IS)	%	15 years savings	Annual savings (B-IS)	%	15 years savings
3 milking tanks	S	3310 €	3139 €	3304 €	6 €	0.18	90 €	-165 €	-5.30	-2475 €
	M	11035 €	10463 €	9292 €	1743 €	15.8	26145 €	1171 €	11.20	17565 €
	L	19863 €	18833 €	16240 €	3623 €	18.24	54345 €	2593 €	13.80	38895 €
5 milking tanks	S	5518 €	5231 €	8229 €	-2711 €	-49.13	-40665 €	-2998 €	-57.30	-44970 €
	M	18392 €	17438 €	23308 €	-4916 €	-26.73	-73740 €	-5870 €	-33.70	-88050 €
	L	33105 €	31388 €	40745 €	-7640 €	-23.08	-114600 €	-9357 €	-29.80	-140355 €

Finally, Table 6 shows the electricity costs analysis. Annual energy cost (A) had been calculated applying Spanish domestic fixed rate tariff, whereas cost (B) had been calculated applying Spanish domestic variable rate tariff (assuming that 50 % of electricity is consumed during off-peak period and 50 % during peak period). Energy costs for ice slurry bases systems (IS) had been calculated assuming that for the 3 milking tanks configuration all the electricity is consumed during the off peak period, whereas for the 5 milking tanks configuration, 58.33 % of the electricity is consumed during the off peak period (14 hours/day) and 41.67 % of the electricity is consumed during the peak period (10 hours/day). As it can be seen in Table 6, only 3 milking tanks configuration allows to achieve economical savings whereas the 5 milking tanks configuration leads to an increase in the electricity bill. On the other hand, as Table 5 shows, the main improvements in TEWI values are obtained with the 5 tanks configuration.

Initial investment costs are not easy to assess and had not been taken into account in the analysis presented in this work. Nevertheless, although these initial costs increase for ice slurry based systems compared to direct expansion system, on the other hand, the capability of instant cooling provided by ice slurry based systems represents an extremely important competitive advantage in milk cooling facilities which also must be taken into account.

6. CONCLUSSIONS

Warming impact, refrigerant charge and electricity costs have been analyzed in 6 different milk cooling facilities. The analysis shows that, in all cases, the replacement of direct expansion systems by ice slurry based systems allows reducing TEWI and refrigerant charge values, whereas only in some cases economics savings are achieved. Further efforts are necessary in order to reduce refrigerant charge and increase efficiency in ice slurry generators.

NOMENCLATURE

GHG	greenhouse gases	*ISG*	ice slurry generator
GWP	global warming potential	*TEWI*	total equivalent warming impact

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