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Development of an Innovative Raw Milk Dispenser Based on Nanofluid Technology

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Abstract: This paper presents the comparative analysis of a traditional raw milk dispenser and an innovative prototype based on nanofluid technology. The traditional raw milk dispenser consists of an off-the-shelf upright air-cooled refrigerator sold on the market, whereas the innovative prototype presents a tank equipped with a serpentine tube jacket operated with Al_2O_3–ethylene glycol aqueous solution nanofluid. The systems are experimentally analysed in the ambient temperature range of 19–35°C to evaluate the energy performance and the temperature control of the milk tank. The innovative prototype is demonstrated to be superior from the point of view of both energy saving and food safety. In fact, the innovative prototype exhibits a 63–70% energy saving with respect to the traditional one. Furthermore, the prototype distributor is able to reach the "safe" temperature of 4°C in about half of the time required by traditional system and it keeps the milk always in the "safe" temperature range 2–3°C, while the traditional distributor displays locally milk temperature higher than 4°C.

Keywords: raw milk dispenser, nanofluid, energy consumption, temperature control, food safety

1 Introduction

In the last years, European farmers have been allowed to sell raw milk directly to consumers; several thousand raw milk dispensers are installed throughout Europe and the market is increasing quickly. The refrigerated raw milk is transferred from large bulk tanks at 4°C to smaller tanks (typically around 200 L) that are placed inside vending machines equipped with an upright refrigerated cabinet. In most of the cases, the milk reservoir is chilled by air coming from a direct expansion finned coil evaporator. The use of air, as secondary fluid, involves poor energetic performance, due to its high convective thermal resistance. Moreover, it also increases cool-down time and temperature gradient inside food, making worse conditions for food safety. A more rational design of this type of refrigerated distributors requires the use of liquid thermal medium as secondary fluid to improve energetic performance and food temperature control. The operating temperatures typical for milk preservation involve the use of brines, such as water–glycol mixtures, which exhibit poor heat transfer performance compared to water. The dispersion of oxide or metallic nanoparticles with high thermal conductivity inside the brine, named nanofluid, greatly improves brine heat transfer capability. The improvement of nanofluid heat transfer capability with respect to the traditional heat transfer medium might be partially explained considering different heat transfer mechanisms, such as Brownian motion of the nanoparticles, nanoparticle agglomeration/aggregation into cluster, thermal conduction in solid phase along the clusters and liquid layering around the nanoparticles/clusters. The experimental and theoretical works carried out till now were not sufficiently systematic to collect a sound amount of coherent and unambiguous data to identify all the specific transport mechanisms and critical parameters of nanofluids. However, the experimental evidence shows the possibility to apply successfully nanofluids as possible heat transfer media in several applications including food industry [1].

To the best author's knowledge, there is no work published in the open literature dealing specifically with raw milk dispenser refrigeration apparatus. Just a few published analyses of refrigeration equipment for milk chilling immediately after milking can be retrieved [2–4] and none of them presented direct measurements of the milk temperature distribution inside the tank or evaluated the effects of temperature gradient on milk quality.

A thorough analysis of different factors affecting the quality of dairy products including raw milk was proposed by Muir [5]. Refrigeration has been demonstrated to have an effect on evolution of the bacterial population of raw milk [6] and it is possible to conclude that raw milk temperature should never exceed 3.5°C along the cold chain, to avoid the risk of formation of thermoresistant extracellular proteases and lipases that will affect the quality of dairy products.

This paper presents the comparative analysis of a traditional raw milk dispenser and an innovative prototype

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based on nanofluid technology. The first one is the off-the-shelf commonly used machine for selling raw milk in Italy consisting of a 200-L stainless steel milk tank placed inside an upright air-cooled refrigerator. The second one is a prototype tank equipped with a serpentine tube jacket operated with Al_2O_3–ethylene glycol aqueous solution nanofluid. The traditional and the innovative dispensers are experimentally analysed in the ambient temperature range 19–35°C to evaluate the energy performance and the temperature control of the milk tank.

2 The tested appliance

2.1 Off-the-shelf system description (traditional system)

The first experimental analysis was carried out on an off-the-shelf upright refrigerator of 575 L internal volume and 828 L external volume (Figure 1a). The refrigeration unit consists of a finned coil condenser, an R404A reciprocating compressor, a capillary tube and a finned coil evaporator. The refrigerator is controlled by ON/OFF operation using a thermostat. The raw milk is stored inside a 200-L stainless steel cylindrical vessel equipped with a stirrer to avoid fatty phases and temperature stratification (Figure 2a). The chilled air is circulated in the rear part of the refrigerator by means of an axial fan installed in the cabinet and then it is recalled from the bottom along the front side of the refrigerated vane. The air circulation brings about the cooling effect over the milk tank. The thermostatic control is driven by an NTC thermistor temperature bulb inserted in a sanitary stainless steel thermowell directly inserted in the lower part of the milk tank at about 5 cm from the tank bottom (letter P in Figure 3). The default set point for the thermostat is kept fixed at 1.6°C.

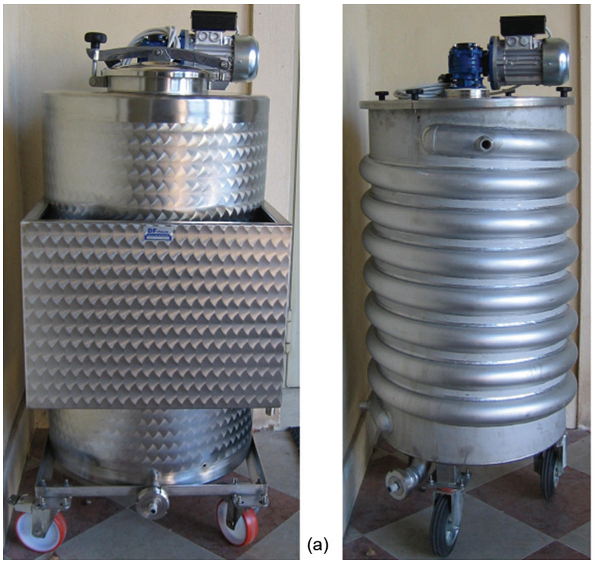

Figure 2: The traditional air cooled milk tank (a) and the prototype liquid cooled one (b).

During the experimental campaign, four T-type thermocouples were installed to monitor the air temperature at the delivery (two sensors), below the tank (in the free space between the refrigerator). A series of 10 T-type thermocouples, named from t1 to t10, were installed inside the milk tank, as in Figure 3, with the scope of monitoring local milk temperature. The system electrical power input was measured by a digital power meter.

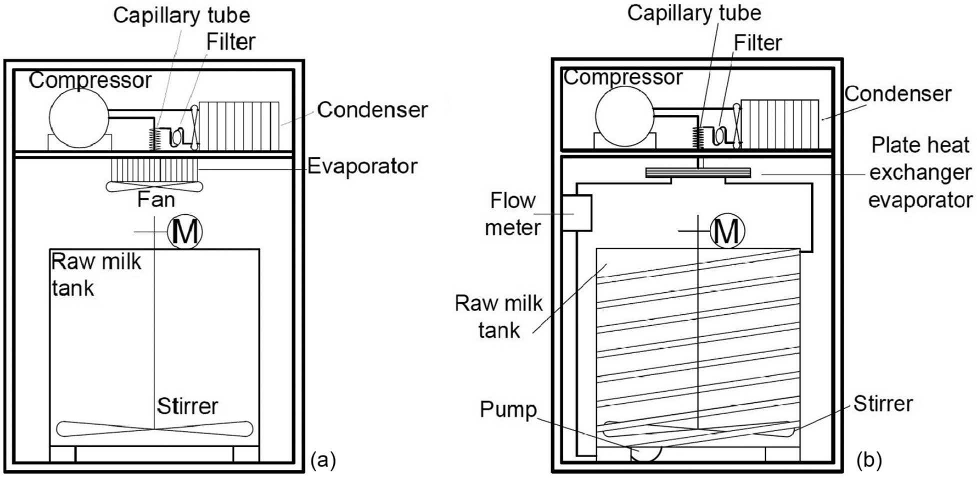

Figure 1: Schematic view of the traditional air cooled raw milk refrigeration system (a) and of the innovative prototype liquid cooled one (b).

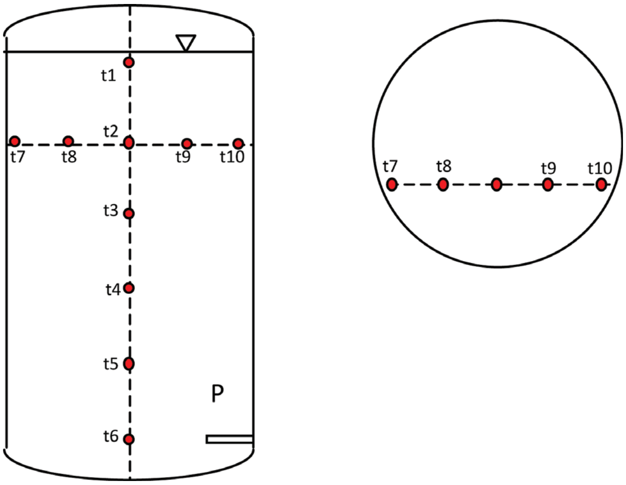

Figure 3: Thermocouples distribution in the milk tank (P indicated the thermo well for thermostat NTC probe).

2.2 Liquid-cooled system description (innovative system)

The original refrigeration unit was modified by replacing the finned coil evaporator with a brazed plate heat exchanger (Figure 1b). This evaporator was designed to achieve less than 3 K difference between the refrigerant dew temperature and the secondary fluid flowing in counter-current to the refrigerant. The capillary tube length was also modified to achieve the optimal working conditions for the new system configuration and the refrigerant charge was optimized. No changes were made for the high pressure side (compressor, condenser and tubing). A stainless steel coiled pipe with semicircular cross section was soldered on the outside of the milk tank wall obtaining a typical outer half-coil jacket (Figure 2b). The innovative system was operated by using Al_2O_3–water/ethylene glycol (77/23 mass%) nanofluid at 1% particle volume fraction as secondary fluid. A detailed description on the nanofluid characteristics is reported in [7]: Table 1 summarizes the relevant characteristics of the nanofluid. The nanofluid was used to improve the relatively poor heat transfer performance of traditional water–glycol mixtures due to their low thermal conductivity and high dynamic viscosity. A small centrifugal pump was installed for nanofluid circulation between the coil jacket and the plate heat exchanger evaporator. A T-type thermopile was installed for measuring the nanofluid temperature difference across the cooling jacket and a T-type thermocouple was used for measuring the nanofluid inlet temperature. An electromagnetic volumetric flow meter was used for measuring the nanofluid flow rate. Ten thermocouples, named from t1 to t10, were installed inside the reservoir, according also in this case to Figure 3. The original stirring system used in the off-the-shelf system was adopted with the same operating schedule and rotational speed to be able to make a comparison of the two systems under the same working conditions.

Table 1: Relevant characteristics of the Al_2O_3–water/ethylene glycol nanofluid.

Nanoparticle structure	Gamma
Nanoparticle purity	99.9%
Average nanoparticle diameter (declared)	10 nm
Average nanoparticle cluster size (at 25 ± 0.01°C)	105 nm
Zeta-potential (at 25 ± 0.01°C)	+58.2 mV
pH (at 20 ± 0.1°C)	3.9

All the measurements are scanned and recorded by a data logger linked to a PC: Table 2 summarizes the main features of the different measuring devices.

Table 2: Specification of the different measuring devices.

Devices	Uncertainty ($k = 2$)	Range
T-type thermocouples	0.1 K	−20/80°C
T-type thermopile	0.05 K	−20/80°C
Digital power meter	1%	0/1,000 W
Magnetic flow meter	0.15% f.s.	60/300 L/h
Data logger	±2.7 μV	0/100 mV

3 Test procedure

All tests were carried out inside a climatic room. Since there is not an established testing standard for raw milk distributors and considering that they are normally installed along the roads inside small shacks without any environmental control, three different ambient temperatures, namely 19°C, 25°C and 35°C, were chosen. Raw milk is normally transferred to the automatic milk distributor from the large shed milk cooler in the farm. Accordingly, the distributor refrigerating unit is sized to maintain the milk temperature between 2°C and 4°C, as it comes from the farm.

In a survey carried out by Sandrucci et al. [8] in 22 farms in the Italian Lombardia region, it was found very often (39% of the cases) that the overall milk temperature inside the shed tank was above 4°C (17% of the cases above 6°C). Based on these results, it was decided to start the test with the fluid inside the tank at 6°C, to leave the compressor running continuously till reaching the set point and then to analyse the system behaviour in preservation mode to complete a time span of 24 h.

Since the test campaign took several weeks it was not possible to use raw milk: it has been demonstrated in the literature that the composition and the thermophysical properties of milk were changing during preservation time and this change was remarkable especially for preservation periods higher than 48 h. Furthermore, the properties of "fresh" raw milk change were dependent on milking season, type of cows and cows' diet among others. With the aim of having a systematic study, from the point of view of heat transfer and its effect on refrigeration system energy consumption, it was decided to use a surrogate fluid. A survey of different industrial fluids was carried out and finally, water/ethylene glycol solution at 90/10 mass% was chosen. Table 3 shows the comparison between the thermophysical properties of two types of milk and the chosen surrogate.

4 Analysis of the results

4.1 Test results for the off-the-shelf system (traditional system)

The off-the-shelf refrigeration system (traditional system) came from the manufacturer with an R404A charge of 290 g and no further adjustment was done by the authors. Before each test, 200 L of surrogate fluid precooled to 6 ± 0.1°C was charged in the reservoir and the reservoir was inserted in the upright refrigerator.

Figure 4 reports the measured temperatures of the milk (surrogate fluid) during the pull-down and preservation operations at 35°C ambient temperature, the worst operating condition. For the sake of clarity, the profiles of t2, t3, t4, t5, t7, t8, t9 are not reported in the graph since they fall between the profiles of t1, t6 and t10 presented in Figure 4. The thermostatic control was left to work in the default conditions predefined by the manufacturer: compressor was OFF when the recorded temperature (from the NTC probe in the thermowell) was equal or below 1.6°C. Compressor was OFF again till when the temperature of the NTC probe reached 3.6°C (2 K of dead band).

Several observations can be drawn from the analysis of Figure 4:

- First, the milk (surrogate fluid) temperature was above 4°C in at least one region of the reservoir for more than 3 h from the start time. This time period was demonstrated by Muir and Phillips [9] to be statistically consistent with the so-called apparent generation time that is the "average time taken for the number of bacteria to double". Accordingly, the milk (surrogate fluid) temperature was higher than 4°C for a time long enough for doubling the bacteria population. Furthermore, the total cool-down time was about 7 h.
- Second, during the OFF period, an evident temperature stratification occurred inside the milk (surrogate fluid). In particular, during the 30 min between two stirrer operations the difference between t1 (placed on the top of the vessel) and t10 (close to the side wall of the vessel) was up to 1.4°C. This was a consequence of the low air temperature delivered by the finned coil evaporator. The works of Muir and Phillips [9] and De Jonghe et al. [10] showed that even temperature differences of about 1°C in the range of 3–6°C could markedly affect the increase of the bacteria population in raw milk. During the experimental tests the vertical temperature gradient (i.e. the temperature difference between t1, on the top, and t6, close to the bottom of the reservoir) was always below 0.8 K. The mixing effect of the stirrer homogenously redistributed the temperature field.
- Third, t6, that closely matched the temperature recorded by the thermostat sensor, was below 4°C for the whole off-period. Nevertheless, because of the stratification, t1 exceeded the safety value of 4°C for about 100 min over the whole preservation period.
- Fourth, the running time of the compressor was 47%.

Table 3: Thermophysical properties of milk and the surrogate fluid.

Property	Water–ethylene glycol	Milk	Milk
	(90/10 mass% $t = 2°C$)	(92% water, 0.4% fat, $t = 2°C$)	(92% water, 7.71% fat, $t = 2°C$)
Density (kg/m^3)	1,014.4	1,039.2	1,036.1
Heat capacity (kJ/kg/K)	4.061	4.098	3.923
Thermal conductivity (Wm/K)	0.526	0.544	0.531
Thermal diffusivity (m^2/s)	1.277×10^{-07}	1.277×10^{-07}	1.306×10^{-07}

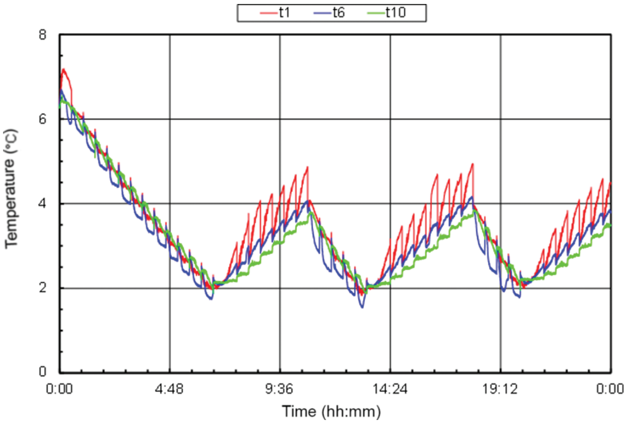

Figure 4: Temperature profile of three thermocouples inside the tank of the traditional system at 35°C ambient temperature.

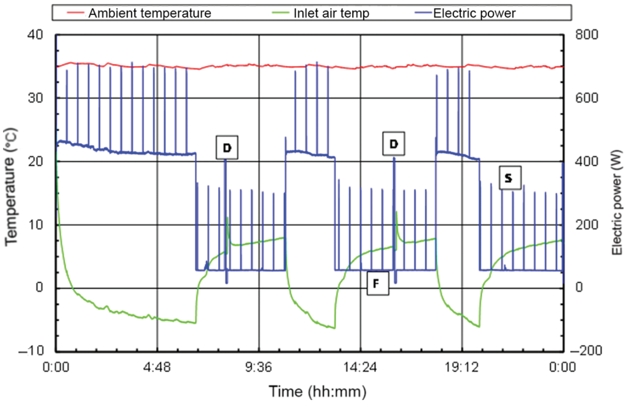

Figure 5: Main operating parameters for the traditional system at 35°C ambient temperature. (D: defrost; F: fan; S: stirrer).

Figure 5 indicates the main operating parameters (temperatures and electric power) at 35°C ambient temperature. One can observe that the temperature of the air delivered from the evaporator falls down to −7.5°C at the end of the on periods. The consequence is a relatively low temperature of the milk (surrogate fluid) close to the vessel walls, with the consequent risk of having temperature of the liquid in contact with the wall close to the freezing point. It can also be seen during the OFF period the inlet air temperature rises up to +7°C and during the defrost operations (letter D) it climbs up to 11.5°C. The defrost operations, as defined by the manufacturer, were time controlled and operated by means of an electrical heater placed inside the evaporator fins. Regarding the electric power consumption, the fan is always in operation, so during the compressor OFF-phase it is possible to stress the fan motor consumption (letter F). Following, the stirrer motor operates for 30 s each 30 min generating a great number of peaks (letter S).

4.2 Test results for liquid-cooled system (innovative system)

Tests were repeated with the prototype innovative system at the same ambient temperatures using the nanofluid as secondary fluids. The secondary fluid was arranged to flow in the upward direction and the volumetric flow rate was fixed at 130 L/h for reducing as much as possible the pressure drops (and accordingly the pump energy consumption) of the nanofluid inside the coil, still having a temperature difference in vertical direction below 1 K. The nanofluid flow inside the coil was always laminar.

Figure 6 reports the temperature profiles of the milk (surrogate fluid) in positions 1, 6 and 10 at 35°C ambient temperature. Also in this graph temperatures t2, t3, t4, t5, t7 and t9 are not reported for the sake of clarity since they fall among t1, t6 and t10 values. During the operation with nanofluid it can be seen that:

- First, the pull-down time is about 2.5 h instead of about 7 h necessary with the traditional unit. Evidently this is a key point in terms of both energy saving and food safety.

Regarding safety issues, it is worth to highlight that Giacometti et al. [11] analysed 100 raw milk samples and found that samples of raw milk taken from vending machines showed a significant increase of total bacteria count in comparison with samples taken from the farm bulk tank. Furthermore, they found that 5% of the analysed samples had at least one pathogen. In another work [12] the same authors analysed the time–temperature history of the raw milk from milking to the consumer in 33 farms. They further analysed the effect of a 5 h period conservation at 7 ± 0.5°C temperature on samples of raw milk originally stored at 4 ± 0.5°C immediately after milking. They found that in 5 h the population count of *Listeria monocytogenes* increased by 5.5%, the *Campylobacter jejuni* population increased by 3.1% and *Salmonella typhimurium* increased by 3.2%. Samples of the same raw milk stored for all the investigated 5 h period at a constant 4 ± 0.5°C showed a negligible change in the population count of the above-mentioned species. Considering that the population count tends to increase with time at constant storage temperature [13], on the basis of the above-mentioned considerations on the behaviour of some pathogens, the reduction of pull-down time observed in the present work surely promotes a safer storage of the raw milk in comparison with the off-the-shelf air-cooled unit.

- Second, during the OFF period the temperature gradient between t1 and t10 is always below 0.4 K and below 0.5 K in vertical direction. The maximum temperature difference occurs during the ON period and is around 1.4 K just for few minutes. So the external nanofluid circulation assures a more uniform temperature distribution in the milk (surrogate fluid).
- Third, in no point the milk (surrogate fluid) temperature exceeds 4°C during the OFF periods.
- Fourth, the running time of the compressor is considerably lower than the traditional unit one.

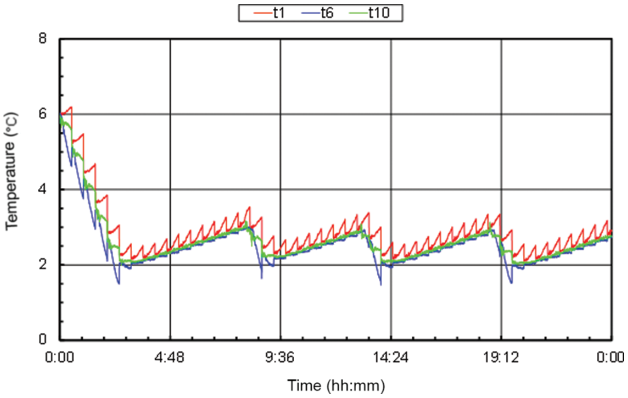

Figure 6: Temperature profile of three thermocouples inside the tank of the innovative system operated by nanofluid at 35°C ambient temperature.

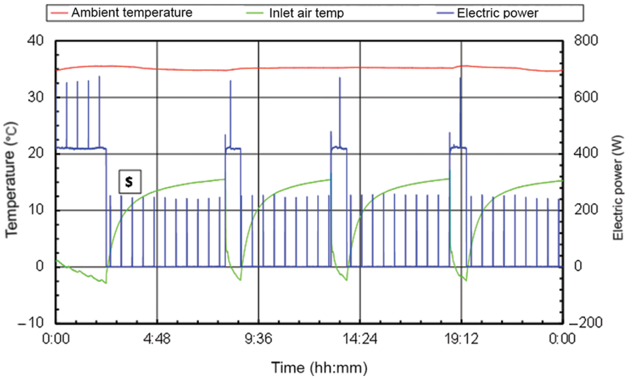

Figure 7: Main operating parameters for the innovative system operated by nanofluid at 35°C ambient temperature. (S: stirrer).

Figure 7 indicates the main operating parameters (temperatures and electric power) at 35°C ambient temperature. The nanofluid leaves the brazed plate evaporator with temperature around −3°C at the end of the compressor ON periods, indicating an evaporation pressure higher than the traditional unit operating under the same ambient conditions (the delivered air temperature was down to –7.5°C). The thermal resistance due to the 2 mm thick AISI 316L wall of the reservoir avoided any possible freezing of the milk (surrogate fluid) in contact with the wall. The pump was not running when the compressor was OFF, so the only energy consumption was the stirrer motor. Obviously, there was no need to run defrost operations.

As a final remark, thanks to the much lower cooling demand due to lower heat input from the ambient (still air inside the refrigerator instead of forced air circulation as in the off-the-shelf unit) and lower internal heat input (pump energy consumption is lower than the fan one), it was possible to reduce the dead band of the thermostat from 2 to 1 K (i.e. compressor OFF period ends when the milk (surrogate fluid) increases up to 2.6°C, being 1.6°C the thermostat set point). This allowed the surrogate fluid to be always below 3.5°C in all the points of the tank for all the preservation period. This temperature value is considered the threshold for a safe preservation of raw milk by De Jonghe et al. [10]. It is worth noticing that, in spite of the 50% reduction of the thermostat dead-band, the compressor started up to three times during the 22 h preservation period with a run-time less than 50% of the original air-to-air unit.

As the final step of the test campaign, with the aim to exploit the potential of the nanofluid to increase the system efficiency in comparison with a conventional brine, the measurements were repeated at the same three ambient temperatures with only ethylene glycol aqueous solution at the same composition of the base fluid (water/ethylene glycol at 77/23 mass%) as secondary fluid.

Figure 8 reports the temperature profiles of the milk (surrogate fluid) in positions 1, 6 and 10, whereas Figure 9 indicates the main operating parameters (temperatures and electric power) of the innovative system operated by ethylene glycol aqueous solution at 35°C ambient temperature. No relevant differences were found for the temperature profiles of milk (surrogate fluid) in the tank between the two secondary fluid options, whereas the two solutions involved different energy consumption.

4.3 Energy analysis

It is interesting to integrate the power consumption over time to obtain the cumulated energy consumption (CEC) during 24 h and the corresponding specific value, per litre of milk (SCEC):

$$\mathrm{CEC} = \int_0^{\tau_{\max}} P \, d\tau \tag{1}$$

$$\mathrm{SCEC} = \frac{\mathrm{CEC}}{V} \tag{2}$$

where $\tau_{\max} = 24$ h.

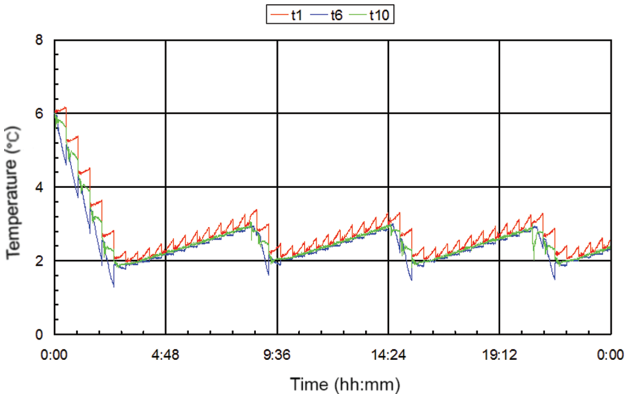

Figure 8: Temperature profile of three thermocouples inside the tank of the innovative system operated by ethylene glycol aqueous solution at 35°C ambient temperature.

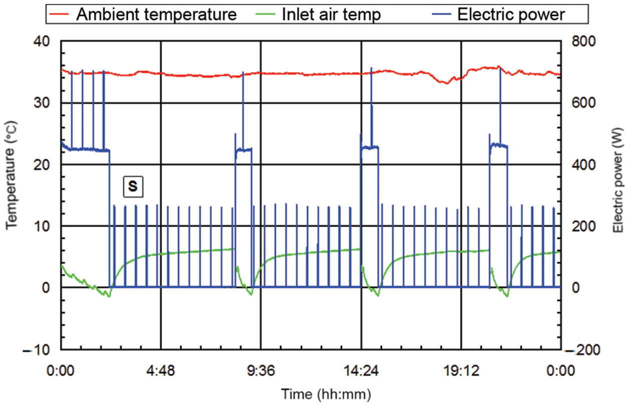

Figure 9: Main operating parameters for the innovative systemc by ethylene glycol aqueous solution at 35°C ambient temperature. (S: stirrer).

Figure 10 shows the comparison of the CEC of the traditional system and the innovative system operated with both nanofluid and water–ethylene glycol mixture at 35°C ambient temperature, whereas Table 4 shows the comparison for all the ambient temperatures tested. The innovative system operated by nanofluid exhibits the best performance showing a 63–70% of energy saving with respect to the traditional system and also a 3–9% of energy saving with respect to the innovative system operated only by ethylene glycol aqueous solution.

The SCEC ranges from 19.5 to 28 Wh/L for the traditional system, from 6.8 to 12.3 Wh/L for the innovative system operated by only ethylene glycol aqueous solution and from 6.3 to 11.3 Wh/L for the innovative system operated by nanofluid. The specific consumption of the innovative system is in line with the values retrieved by Brush et al. [14] who reported "energy intensity" for milk preservation refrigeration in the United States of 11.8 Wh/L in the preservation phase, whereas the data of the traditional system are relatively higher.

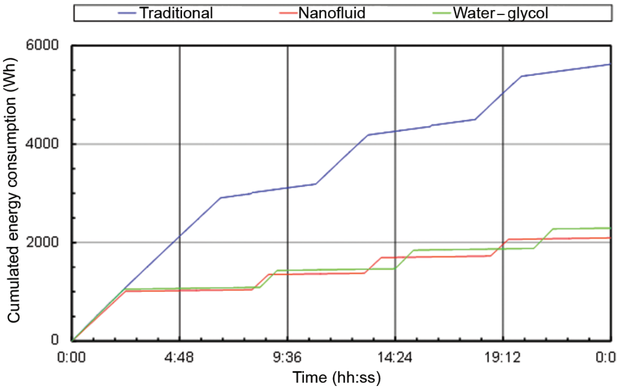

Figure 10: Cumulated Energy Consumption (CEC) of the different systems at 35°C ambient temperature.

Table 4: Cumulated energy consumption (CEC) of the different systems.

Ambient temperature	Traditional (Wh)	Water–glycol (Wh)	Nanofluid (Wh)
19°C	3,950	1,297	1,180
25°C	4,263	1,445	1,404
35°C	5,694	2,294	2,095

The positive behaviour of the innovative system operated by nanofluid with respect to that operated by brine is probably linked to the heat transfer enhancement in the serpentine cooling jacket under laminar flow. The results here reported represent just a first brick for the exploitation of actual behaviour of nanofluids inside half-pipe coiled jackets and further analysis is recommended.

5 Conclusion

This paper presents the comparative analysis of a traditional raw milk dispenser consisting of an off-the-shelf upright air-cooled refrigerator and an innovative prototype which presents a tank equipped with a serpentine tube jacket operated by Al_2O_3–ethylene glycol aqueous solution nanofluid. Both the systems were tested for 24 h at three different ambient temperatures (19°C, 25°C and 35°C) including a cool-down from 6°C to 4°C of the milk (surrogate fluid).

The innovative system operated by nanofluid demonstrated superior performance as follows:

- It requires only one-third of the energy consumed by the traditional system.
- It exhibits also a 3–9% energy saving with respect to the operation with only water–ethylene glycol mixture as secondary fluid.
- The cool-down time is about 60% lower.
- The milk (surrogate fluid) temperature is always in the optimal range (2–3°C) during the preservation period, whereas in the traditional system the milk temperature rises over the “safety” limit of 4°C.
- It allows a much lower temperature gradient in the milk (surrogate fluid) (less than 1 K, instead than about 1.5 K for the traditional system).

Nomenclature

CEC	cumulated energy consumption (Wh)
D	defrost
F	fan
k	coverage factor
M	motor
P	electric power (W)
S	stirrer
SCEC	specific cumulated energy consumption (Wh/L)
t	temperature (°C)
V	total milk volume (L)
τ	time (s)

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