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Mathematical Models for Predicting Maximum Cooling Load ofAC Vapour CompressionMilkSolar Refrigeration Systems

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Abstract: *The mismatch between solar energy availability and the cooling load energy demands for AC solar refrigeration systems in different geographical locations complicates the design and sizing of milk solar refrigeration systems components. This is caused by variation seasonal solar insolation and different levels of global solar insolation. In this study, three different sizes AC milk solar refrigeration systems, have been investigated for maximum cooling loads developed from the refrigeration systems when exposed to varying levels of solar insolation in Nakuru Kenya.Regression models were developed for predicting maximum cooling loads delivered from the milk solar refrigeration systems based on available mean daily solar insolation of the location. The predictive models developed is useful tools in the design and sizing of milk solar refrigeration componentsbased on solar insolation available at any global location. Three Solar refrigeration systems were fitted with AC reciprocating compressors of capacities'; 350W, 250W,200W and were investigated for maximum cooling loads under varying mean daily solar insolation. Four PV panels each of 200 Wp connected via an inverter provided the power required to operate the compressors in each of the refrigeration system.An innovative control unit operated the refrigeration systems dependent on the solar insolation level available in the day.Temperature profilesof water placed in the centralwater can, and the amount of ice formed were used to determine the maximum cooling load of each refrigeration system with, based on solar radiation available. The regression cooling curve generated by each system was used in developing the mathematical cooling load prediction models based on available solar insolation of Nakuru*

Conclusion:*The results showed that the maximum cooling loads obtained from the solar refrigeration systemsis dependent on the annual mean daily solar insolation of a specific location and the capacity of the refrigeration system compressor.The mathematical models showed a strong correction ofcoefficient of between 0.958 and 0.908when validated with actual solar refrigeration cooling loads.*

Key Words: *Cooling loads; Solar insolation; AC solar refrigeration system.*

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I. Introduction

The unpredictable and intermittent nature of global solar insolation which provides solar energy that is dependent on weather conditions, seasons and global locations of a site. This causes a major drawback in the application of solar energy technologies, resulting in poor performance and low efficiency on standalone milk solar refrigeration system and rejection of load at some point,[1]Solar energy effective utilization depends upon the assessment of solar insolation planning, design and selling their energy technology [2]Just as the fossil-based energy, industries rely on exploration and proven reserves for economic support for energy markets. In solar based renewable energy technologies. such as milk solar refrigeration systems the basic resource is solar radiation. [3]showed that uncertainties

in life cycle saving for solar photovoltaic (PV) system are lineally correlated to global variations and uncertainty in solar insolation. [4]stated that the milk solar refrigeration systems reliability can improve performance optimized by reduction in energy mismatch leading to more efficient and economical systems. Most of the current solar technology store the harnessed solar energy in batteries, which increases the reliability of the technologies but has disposal challenges after useful life [5]. [6]indicated that the challenge on milk cooling was due to the short period of less than three hours required to cool the milk to 4°C. This resulted in the need of fast cooling refrigeration system and hence most low speed and low performance refrigeration systems have limited application in milk cooling A model for predicting the cooling loads generated by solar driven milk cooling refrigeration system, based on the solar energy availability in a specific geographic location, would consequently reduce design inaccuracy and optimize on the efficiency and enhance the affordability and availability of the system to most SMEs in rural set up of the developing economies. The harnessing and storage of excess solar energy available in peak periods and its conversion to sensible thermal energy in ITS, would enable provision of the milk cooling energy during low solar energy availability. This process would significantly ensure steady and reliable milk cooling.

II. Materials and Methods.

This research study was carried out in the tropical region of Kenya at Nakuru town in Nakuru county at of longitude of 0.284^{O} S and a latitude of 36.02^{O}E.

The experimental setup constituted the equipment for measurement of daily solar insolation and the solar refrigeration cooling loads generated by three refrigeration systems under varying solar insolation. Three milk solar refrigeration systems were fitted with AC compressors of size; 350 W, 250 W and 200 W, designed and fabricated as prototypes to cool 20 kg of water as a substitute of milk from 36^{O}C to a minimum of 4^{O}C in less than 3 hours. The compressors in each of the refrigeration system was connected to 200 Wp polycrystalline PV solar panels which provided the required power to the systems via inverters. The cooling vessels in which the cooling loads were to be determined for each of the refrigeration system consisted of a centrally place milk cooling can, surrounded by an outer 15kg ice container, an outer jacket of 35% concentrated brine solution in which the evaporator of each refrigeration system was immersed to effect the cooling. A 60mm extruded light form of 21.5kg/m^{3} density polystyrene insulation, was used to reduce heat gains and losses from the vessel. Figure 1 shows the cross section of the milk cooling vessel used in the milk solar refrigeration system.

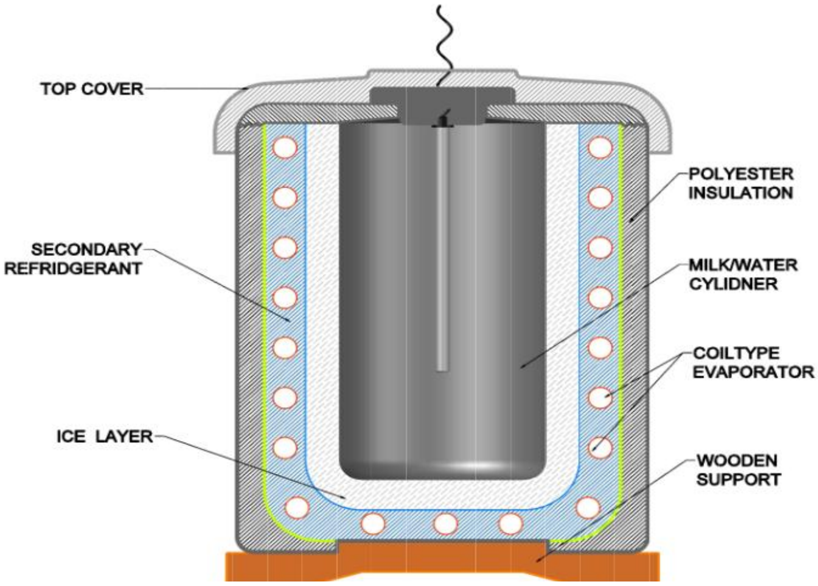


Figure1. Cross section of milk cooling vessel

The cooling loads generated by each refrigeration system was monitored by use of three PT-100 thermal sensors of accuracy $\pm 0.01^{o}C$, immersed in the water can to measure the temperature profile from 9am to 4 pm.The temperature drop for each system was recorded by A COMBI-LOG 1021 data logger, at a frequency of 15 seconds. The mass of ice produced from water in the ice container was determined by draining and weighing the water that remained in the ice container at the end of each day. The difference between the water collected and the 15 kg of water initially at the beginning of the cooling process provided the mass of ice formed.

The ‘on’ and ‘off’ switching of each compressor, was dependent on the solar radiation available which was detected and actuated an innovative control unit to start and stop the operation of each refrigeration system. A 30 Wp pilot solar panel was placed adjacent to the pyranometer to generate a voltage depending on the intensity of solar radiation. Using a PLC program, the voltage was converted to the corresponding solar insolation in W/m^{2} and recorded by a COMBILOG data logger at a frequency 15 seconds. Depending on the level of solar radiation the innovative control unit generated a voltage signal commensurate to the level of solar radiation, and regulated the ‘on’ and ‘off’ operating status of 200 W, 250 W and 350 W of the milk solar refrigeration systems. Figure 2 Shows setup of equipment for the three solar refrigeration systems.

The milk solar refrigeration system which provided maximum cooling loads based on the mean daily solar insolation available at a location, was obtained by establishing the cooling loads of three different refrigeration systems integrated with compressor of different sizes, when exposed to varying solar insolation for the same period of time. This was done by observing that the temperature in the milk can dropped from 33^{O}C to

4^{O}C in less than 3 hours, and measuringthe maximum mass of ice produced in each refrigeration system at the end of each day. The process was carried out under varying mean daily solar radiation for a period of one year from May 2018 to May 2020.

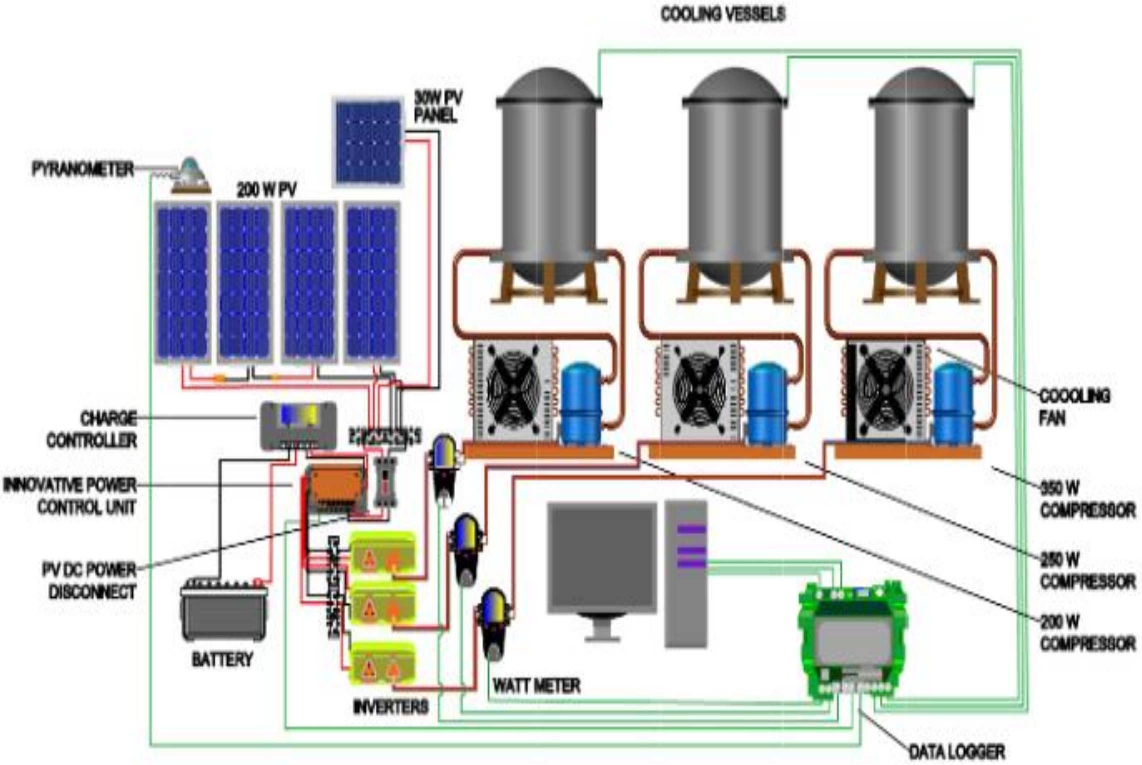


Figure 2. Equipment for solar Refrigeration systems setup

III. Results

The 200W refrigeration system indicated an operation mean daily solar radiation between 200.281 W/m^2 to 414.382 W/m^{2}band, while the 250 W had an operation mean daily solar radiation between 420.715 W/m^2 to 580.847 W/m^{2}band and lastly the 350 W refrigeration system was from 580.391 W/m^2 to 664.358 W/m^{2}band. The minimum, mid and maximum solar radiation for each band was established from the minimum temperature when ice started forming, mid temperature when amount of ice was half full in the milk can, and the maximum temperature corresponding to maximum amount of ice formed as recorded by the data logger as in table 1

Table 1. Compressor mean daily solar operating bands

Compressor size (W)	Operating Mean Solar Radiation band (W/m^2)	Mean Daily solar Insolation (W/m^2)		
		Minimum	Average	Maximum
200	100.281-420.715	213.653	350.682	414.382
250	420.715-580.391	446.988	497.548	570.847
350	580.391-670.803	580.391	623.362	664.358

Figure 3 shows the cooling curves for the 200 W, 250 W and 350 W milk solar refrigeration systems when plotted under varying solar insolation. It was observed that the 200 W refrigeration system had the highest cooling rate in the morning hours with a maximum cooling load of 0.245 kWh. Again, this was as a result of the small capacity refrigeration system's compressor that allowed the system to start with low solar radiation levels as compared to the others higher capacity refrigeration systems. The 250 W refrigeration system, had lower cooling rates compared to the 200 W refrigeration system in the morning hours. The highest cooling rate occurred at solar insolation between 450 W/m^2 and 570 W/m^2. This was attributed to availability of sufficient solar radiation required to start and maintain the running of the250 W compressor. The 250 W refrigeration system showed the highest cooling load of 0.262 kWh which was the highest of the three refrigeration systems. The mean daily solar insolation for this particular day was 414.37 W/m^{2}which meant that the larger number of hours of the day, experienced solar radiation of between 420 W/m^2 to 570 W/m^2 hence providing largest cooling load, than the other refrigeration systems.The lowest rate of cooling in the morning hours was experienced in the 350 W refrigeration system for the three refrigeration systems. This was attributed to insufficient solar insolation below 570 W/m^2 in the morning hours to start the operation of the 350 W compressor integrated in the refrigeration system. The highest cooling rate of this system was experienced when the solar insolation was above 580 W/m^2. The highest cooling load recorded by the 350W refrigeration system was 0.258 kWh as indicated in table 1. The 250 W solar driven refrigeration system exhibited the highest cooling load for the three refrigeration systems. [7]and [8]observed similar trend when experimenting of DC refrigeration compressors.

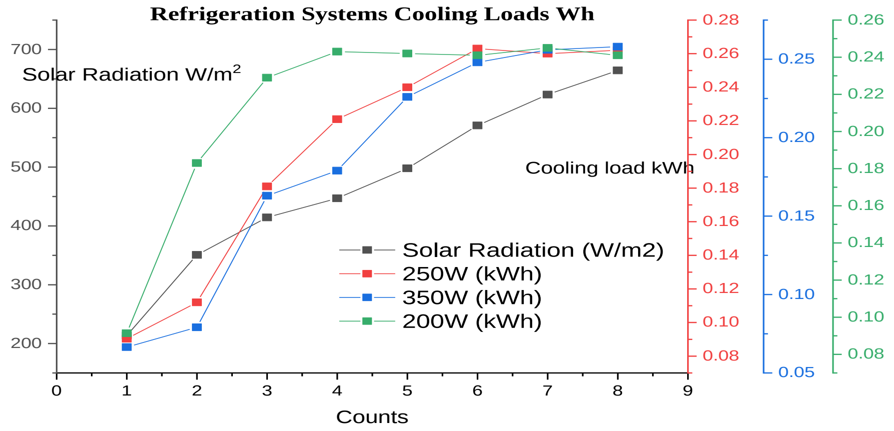


Fig3. Milk Solar refrigeration systems cooling loads

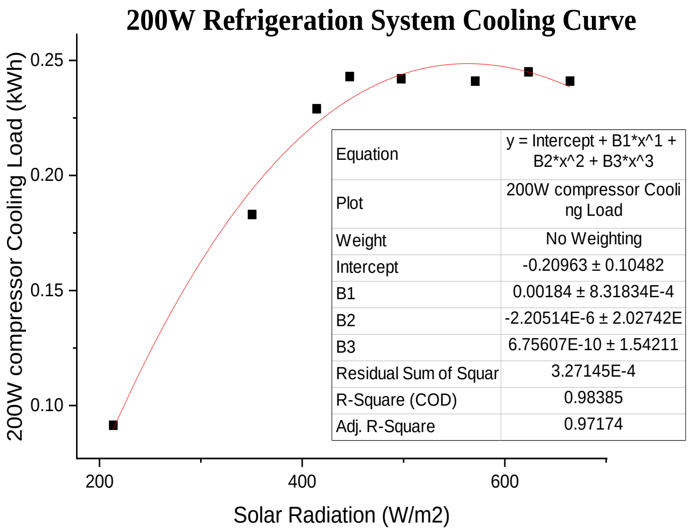
Apart from direct cooling of milk when there was sufficient solar insolation, the milk solar refrigeration systems ware also designed to cool milk for a minimum of 3 days, when there was insufficient solar radiation occasioned by weather and seasonal changes in the course of the year. The thermal cooling load needed for milk cooling in the event of low solar radiation was to be provided by ice banks, produced when there was sufficient solar radiation. Table 2 indicates mass of ice produced in the cooling process of the three refrigerators under varying solar radiation.

Table 2. Mass of ice formed in cooling process

Mean Daily Solar Radiation W/m^2	**Compressor sizes W and Mass of ice formed kg**		
	200 W	**250 W**	**350 W**
213.651	4.38	4.18	3.16
350.682	5.78	5.43	3.26
414.368	6.27	6.78	4.34
446.985	6.63	6.89	5.92
497.848	6.71	7.03	6.88
570.848	6.73	7.24	6.91
623.362	6.72	7.35	6.95
664.358	6.74	7.34	6.94

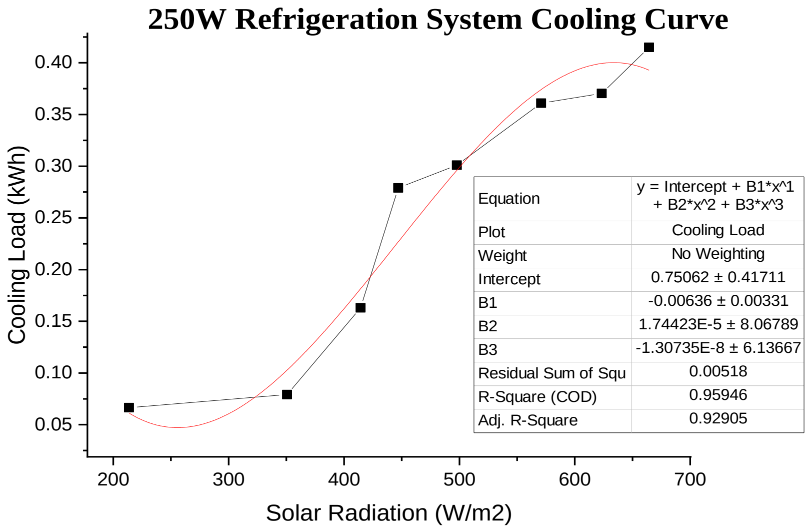
Table 2 shows the mass of ice formed by each of the three refrigeration systems on 3rd January when the mean daily solar Insolation was 414.37 W/m^2, while figure 3 shows the profiles of the mass of ice producedby the three systems. From table 2 and figure 4 it was observed that the 200 W refrigeration system produced the maximum amount of ice equivalent to 5.78 kg between the solar insolation of 213.651 W/m^2 and 350 W/m^{2}compared to the other refrigeration system. The 250 W refrigeration system generated the largest amount of ice of 7.35 kg when the solar insolation band was between 414.368 W/m^2 and 623.362 W/m^2. The largest refrigeration system with the highest compressor of 350 W, generated 6.95kg of ice above a solar radiation band of 623.362 W/m^2. It was thus noted that the 250 W milk solar refrigeration system generated the largest amount of ice of 7.35 kg compared to the other refrigeration systems. This was due to a greater number of hours the 250 W refrigeration system was in operation and the capacity of the compressor. Victor Torres *et al.*, (2015) while experimenting on a small milk cooling system with ice storage, obtained 6 kg of ice when the system operated with a mean solar radiation of about 414 W/m^2. It was observed that the three refrigeration systems obtained the maximum cooling loads at different solar insolation bands. The 200W refrigeration system had a maximum cooling load of 0.243 kWh and ice mass of 6.26 kg at a solar insolation band of between 213.651 and 446.985 W/m^2. The 250 W refrigeration system had a maximum cooling load of 0.263 kWh and ice of mass 7.35 kg at a solar radiation band of 446.985 W/m^2 and 570.848 W/m^2. the 350 W refrigeration system showed a maximum cooling load of 0.258 kWh and ice of mass 6.95 above 664.358 W/m^2

Each of solar refrigeration system, exhibited minimum and maximum cooling loads and a corresponding mass of ice formed, at different mean daily solar radiation operating bands, the cooling load for each refrigeration system when plotted separately, showing regression cooling loads curves as indicated in figures. 4, 5 and 6.



Equation	y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Plot	200W compressor Cooling Load
Weight	No Weighting
Intercept	-0.20963 ± 0.10482
B1	0.00184 ± 8.31834E-4
B2	-2.20514E-6 ± 2.02742E
B3	6.75607E-10 ± 1.54211
Residual Sum of Squar	3.27145E-4
R-Square (COD)	0.98385
Adj. R-Square	0.97174

Fig 4. Cooling load curve for 200W refrigeration system



Equation	y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Plot	Cooling Load
Weight	No Weighting
Intercept	0.75062 ± 0.41711
B1	-0.00636 ± 0.00331
B2	1.74423E-5 ± 8.06789
B3	-1.30735E-8 ± 6.13667
Residual Sum of Squ	0.00518
R-Square (COD)	0.95946
Adj. R-Square	0.92905

Fig.5 Cooling load curve for 250W system

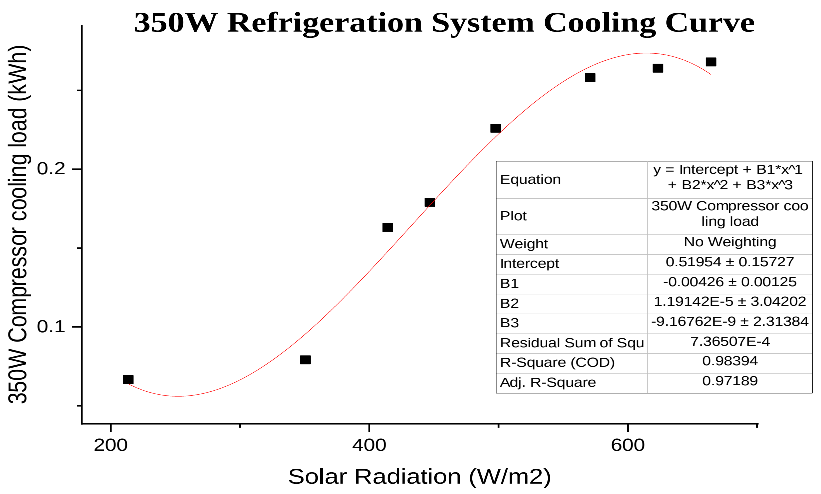


Fig.6 Cooling load curve for 350W system

The cooling load regression curves were used to develop the mathematical regression models for each refrigeration system based on the solar Insolation. From the cooling load curves in figures 4, 5 and 6, the three-refrigeration system of 200 W, 250W and 350W generated the mathematical regression cooling models as shown in equations 1.0, 2.0 and 3.0

$Q_L = -0.2096 + 0.00184S_R - 6(S_R^2) + 6.75E - 10(S_R^3)1.0$

$Q_L = 0.5195 - 0.0627S_R + 1.744E - 5(S_R^2) - 1.307 - 8(S_R^3)2.0$

$Q_L = 0.5195 - 0.004265S_R + 1.1914E - 5(S_R^2) - 9.176E - 9(S_R^3)$ 3.0

where; Q_L *is cooling load kWh,* S_R *is the mean daily solar in* W/m^2

The three models were validated by subjecting the solar panels at different solar radiation. Table 3shows the models predicted cooling loads and the measured cooling loads of the three milk solar refrigeration systems.

Table 3. Cooling loads for refrigeration system and prediction models

Solar Radiation. W/m^2	Cooling Loads for system and models					
	200 W system	200 W Predicted	250 W system	250 W Predicted	350 W system	350 W Predicted
346.146	0.181	0.191	0.113	0.096	0.087	0.092
436.446	0.248	0.23	0.147	0.21	0.159	0.168
473.276	0.246	0.249	0.241	0.261	0.196	0.2
501.188	0.257	0.246	0.278	0.298	0.241	0.223
543.459	0.251	0.247	0.296	0.347	0.244	0.252
609.296	0.237	0.246	0.387	0.394	0.252	0.273
629.678	0.253	0.243	0.399	0.398	0.265	0.272
652.791	0.248	0.24	0.398	0.395	0.268	0.266
683.189	0.246	0.234	0.381	0.378	0.266	0.247

Statistical analysis on the performance of the cooling load predicting models was done using coefficient of correlation in each refrigeration system. The correlation coefficients obtained for the 200 W, 250 W and 350 W milk solar refrigeration systems were 0.845, 0.9413 and 0.956 respectively.[8] observed similar values on small milk systems

IV. Conclusion

It was observed that the cooling load and the amount of ice produced by the milk solar refrigeration system was governed by the mean daily solar radiation available and the capacity of the refrigeration system compressor. The cooling load curve generated by each refrigeration system showed different optimal cooling point, and hence the three refrigeration systems of 200 W, 250 W and 350 W were considered separately in developing the cooling load mathematical models. Regression cooling load model were developed from the cooling load curves generated by the three refrigeration systems

References

[1]. Coste,E., EftimieG. and Serban,P. (2007), Empirical model for estimating global radiation for Brasov urban area, Journal of Information Engineering and Application, 10(2),2224-5782

[2]. Pongsid,S, Santha,G. and Supachart.C. (2001), Review of Vapour Absorption Refrigeration Technologies. Renewable and sustainable Energy Journal, (5),

[3]. Lopez,G, Rubio,M. andButles.F. (2009), Estimation of hourly direct normal Radiation from measured lobal solar radiation in Spain, Renewable Energy, (21), 175-186.

[4]. Sendanayeke,S., Miguntana,N.P. and Jayasinghe.M. (2014), Estimating Incident Solar Radiation in Tropical Islands with Short Term Weather Data, European Scientific Journal, 3 (2014), 1857-2881

[5]. Lovell,S. and Vickers,L.E. (2005), Cogeneration of heat and electricity in spray drying plant, Progress in Photovoltaic: Research and Application, 12(6), 467-479.

[6]. DabasJ., SudhirK., DodejaA.k., and Kasan, K.S. (2014), Modeling of Horizontal Shell and Tube Dry Expansion Refrigeration Evaporator, International Journal of advance Mechanical Engineering, 3234 (4), 33-54.

[7]. Toress- Toledo, V., Meissner,K., Coronas,. A., Muller.J (2016), Photovoltaic milk cooling as a business opportunity in the tropics, OTTI International Conference on solar Energy Technology in development cooperation, Frankfurt, Germany

[8]. Torres- Toledo, Victor T, Klaus, and Coranas (2015), Performance characterization of a small milk system with ice storage for PV application. International Journal of Refrigeration (60) 57-63

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