Experimental Analysis of Solar Refrigeration System

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1. Abstract

Solar energy is one of the most promising energy sources that can replace the conventional energy sources at no or low cost. In current times most part of the available energy sources is utilized for satisfying the refrigeration and air conditioning needs, which increase the burden on fuel and other sources. Solar refrigeration is a cost-efficient alternative for refrigeration during the daytime.

This paper explains the prototype 40-litre solar refrigerator designed and developed for monitoring its performance in Indian climate and evaluates economic feasibility and affordability in domestic, commercial and industrial applications. The test results obtained shows that the prototype setup confirms the cooling abilities and thus makes it suitable for refrigeration in domestic and commercial area.

2. Introduction

Solar energy finds its applications in the diversified areas like solar refrigeration, solar pumping, solar water heating, solar drying, solar photovoltaic lighting system etc. These systems are more popular because of they provides lot more benefits to the user in terms of cost, maintenance, portability, performance and usability. These systems can be used with or without any storage equipments.

This prototype solar refrigeration system refrigerator uses the photovoltaic power for performing its operations. The system is designed with battery storage for enhancing the performance of the refrigerator. The system consists of 40 litres of refrigerator box. The refrigerator consists of 48-watt, AC compressor. The compressor get power from battery though inverter. Inverter converts the 12V dc supply into 260V ac supply by amplifying the voltage. The photovoltaic panels are directly connected to the 12-volt battery. The battery stores current coming from solar panel.

3. Mathematical Modelling of Solar Refrigerator

3.1 Problem Formulation

In formulation for our prototype refrigerator (Figure 3.1) we have concentrated on the following factors...

1. The natural convection heat transfer mode is considered.
2. The refrigerator cabinet has been divided into vertical and horizontal surfaces.
3. Pressure variations in the direction perpendicular to the plate are neglected.
4. The viscous forces are assumed to be negligible.
5. The radiation heat transfer to the cabinet is neglected.

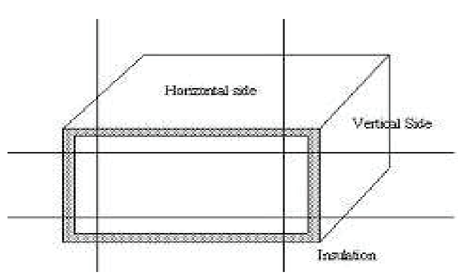

Figure 3.1: Refrigerator box

The formulation requires the determination of heat transfer coefficient of air inside and outside of the refrigerator cabinet that concerns with the horizontal and vertical surfaces and the total amount of heat transfer inside and outside of the refrigerator for deciding the cooling load. For analysing the cooling load and for mathematical modelling of refrigerator, we selected the method of boundary layer analysis for natural convection.

3.2 Heat transfer coefficient of outside air on vertical surface

Assume the flow of air is laminar over the flat vertical surface (Figure 3.2). Thus the continuity, momentum and energy equations are…

$$N_{um} = 0.68 + 0.678 R_a^{\frac{1}{4}} \frac{1}{\left[1 + \left(\frac{0.492}{P_r}\right)^{\frac{9}{16}}\right]^{\frac{4}{9}}} \qquad \text{at } R_a < 10^9$$

The heat transfer coefficient of outer air is given by $h_x = \dfrac{N_u k}{L}$

and the heat transfer rate is given by $Q = UA\Delta T$; $Q = \dfrac{\Delta T}{R} = \dfrac{T_{out} - T_{surf}}{R}$

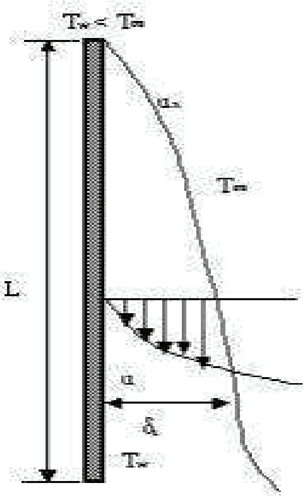

Figure 3.2: Thermal boundary layer on vertical surface heat transfer coefficient of outside air

3.3 Heat transfer through refrigerator wall

Refrigerator wall consists of insulation packed between two mild steel plates. To determine the heat transfer rate through wall we apply the principle of Cartesian coordinate for conduction heat transfer (Figure 4.3).

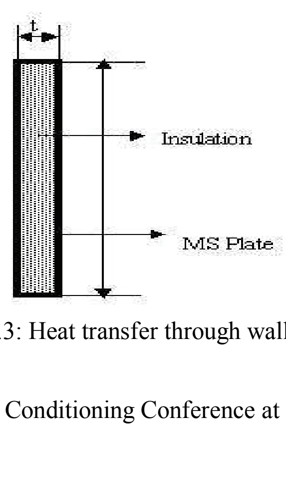

Figure 3.3: Heat transfer through wall

The heat transfer through the refrigerator wall is given by

$$Q = \frac{\Delta T}{R} \qquad R = \frac{2L_{msplate}}{k_{msplate}A} + \frac{L_{insul}}{k_{insul}A}$$

3.4 Heat transfer coefficient of inside air on vertical surface

The mathematical model for heat transfer coefficient of inside air along the vertical surface (Figure 3.4)is same as that of outside air, only difference is that the $T_w > T_\infty$

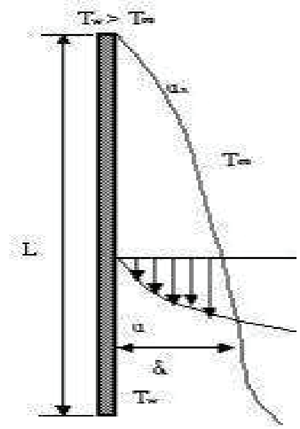

Figure 3.4: Thermal boundary layer on vertical surface heat transfer coefficient of inside air

$$G_r = \beta g \frac{T_{wi} - T_{\infty i}}{\vartheta^2} L^3 \qquad P_r = \frac{\mu C_p}{k} \qquad N_{um} = 0.68 + 0.678 R_a^{\frac{1}{4}} \frac{1}{\left[1 + (\frac{0.492}{P_r})^{\frac{9}{16}}\right]^{\frac{4}{9}}}$$

Thus, heat transfer coefficient of inside air is given by $h_{ix} = \frac{N_u k}{L}$

3.5 Heat transfer coefficient of outside air on horizontal surface

For determining the mathematical expressions the method of boundary layer equation is considered on horizontal surface (Figure 3.5).

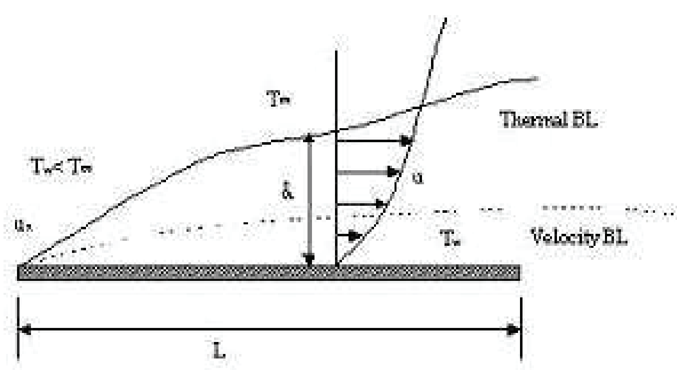

Figure 3.5: Thermal boundary layer on horizontal surface

The Nusselt number for free convection over horizontal surface is

$$N_u = 0.13(G_r P_r)^{\frac{1}{3}} \quad \text{at } G_r P_r < 2\text{x}10^8 \quad \text{thus} \quad N_u = 0.13 R_a^{\frac{1}{3}}$$

The heat transfer coefficient is $h_x = \dfrac{N_u k}{L}$

Total heat transfer rate (total cooling load) is obtained as

$$Q_{total} = 3Q_{vertical} + 2Q_{horizontal}$$

Other parameters are computed as

$k_{ins} = 0.155$ w/mK $\qquad$ $k_{msp} = 11$ w/mK

Area of vertical surface = $A_{vert} = 0.0968\text{m}^2$

Area of horizontal surface = $A_{horz} = 0.193\text{m}^2$

The total heat transfer rate equation can be expressed as

$$Q_{total} = 3\frac{\Delta T}{R_v} + 2\frac{\Delta T}{R_H}$$

Taking into consideration the heat leakage and the required TR of cooling, it is estimated that the prototype refrigerator for **120W cooling load** capacity needs to be designed.

4. Performance Testing

The refrigerator was operated using an AC compressor and draws power from storage battery through inverter, which converts the 12V DC in 260V AC supply, by amplifying the voltage. The battery is connected to the photovoltaic panels. For testing, 48W panels are used with current ratings of 1.9 to 2 amps–hr and voltage ratings of 19 to 24V. The system performance (Figures 4.3 to 4.7) in hot and humid conditions of Nagpur (INDIA) at an average surrounding condition of 42°C are summarized below

Time (min)	Voltage (V)	Current (Amps)	Ambient Temperature (°C)	Watt Stored	Watt-hr
0	19	1.9	42	36.1	32.08
15	18	1.9	42	34.2	
30	19	1.9	43	36.1	
45	18	1.2	43	32.4	
60	18	2	42	21.6	
75	20	2	42	40	37.55
90	19	2	42	38	
105	19	1.9	45	38	
120	18	1.9	45	34.2	
135	18	1.8	45	34.2	33.325
150	16	1.9	43	28.8	
165	18	1.9	44	34.2	
180	19	1.2	44	36.1	
195	17	1.8	43	20.4	31.29
210	20	1.8	43	36	
225	19	1.92	43	34.2	
240	18	1.8	43	34.56	
255	18	1.79	43	32.4	30.252
270	20	1.4	42	35.8	
285	19	1.4	42	26.6	
300	19.5	1.6	42	27.3	
315	19.5	1.6	41	31.2	32.05
330	19.5	1.6	41	31.2	
345	18	1.6	41	38.8	
360	18	1.55	41	27	
375	19	1.9	42	36.1	35.15
400	18	1.9	42	34.2	

Figure 4.1: Testing with battery charging with solar panels

Time (min)	T_r (°C)	Pressure (psi)		Voltage (V)	Current (Amp)	T_c (°C)		T_e (°C)		COP
		P_c	P_e			(Tco)	(Tci)	(Teo)	(Tei)	
0	34	200	15	240	1.2	32	40	34	30	2.48
5	30	200	17	240	1.25	33	49	30	20	3.05
10	26	210	17	230	1.2	33	55	26	18	2.73
15	20	210	17	230	1.2	33	60	20	11	2.60
20	15	210	18	230	1.2	37	62	15	11	2.53
25	11	210	18	230	1.2	37	62	11	08	2.83
30	10	230	18	230	1.2	38	61	10	08	2.58
35	05	230	20	231	1.2	39	61	05	06	2.55
40	01	230	20	230	1.2	39	62	01	06	2.58
45	-01	230	20	230	1.2	39	61	-41	06	2.55
50	-03	230	23	230	1.2	39	62	-43	05	2.45
55	-05	240	23	230	1.2	33	62	-45	07	2.62
60	-06	245	23	230	1.2	33	61	-46	05	2.54
65	-09	245	23	230	1.2	33	64	-49	01	2.78
70	-09	245	26	230	1.2	40	62	-49	01	2.60
75	-10	250	26	230	1.2	40	62	-.0	01	2.65
80	-10	250	27	230	1.2	40	61	-.0	-01	2.75
85	-11	250	27	230	1.2	40	60	-.1	-01	2.89
90	-12	250	27	230	1.2	41	60	-.2	-02	2.74
95	-13	250	29	230	1.2	41	61	-.3	-03	2.83
100	-13	250	29	230	1.2	42	63	-.3	-03	2.75
105	-14	255	30	230	1.2	42	61	-.4	-05	2.77
110	-14	255	30	230	1.2	43	62	-.4	-06	2.71
115	-15	255	30	230	1.2	44	61	-.5	-07	2.93
120	-15	260	30	230	1.2	44	60	-.5	-07	2.93
125	-15	260	30	230	1.2	44	60	-.5	-08	3.38
130	-15	260	31	230	1.2	43	61	-.5	-08	3.38
135	-15	260	31	230	1.2	43	61	-.5	-09	3.38

Figure 4.2: Testing with battery storage at ambient temperature

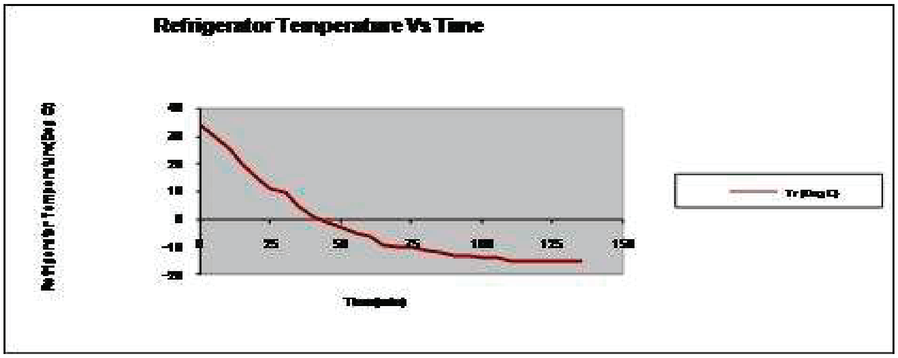

Figure 4.3

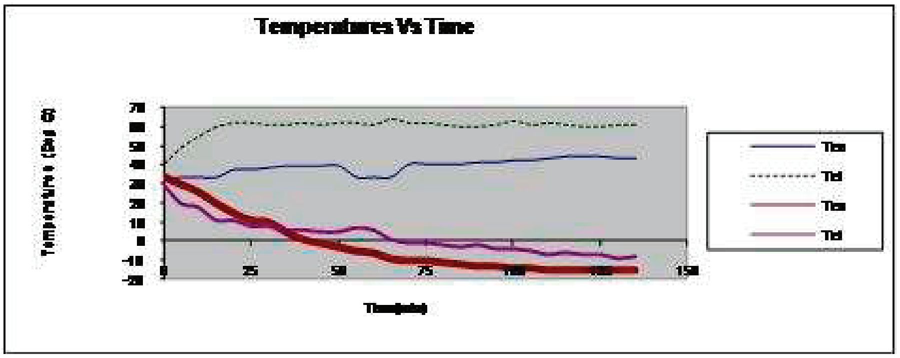

Figure 4.4

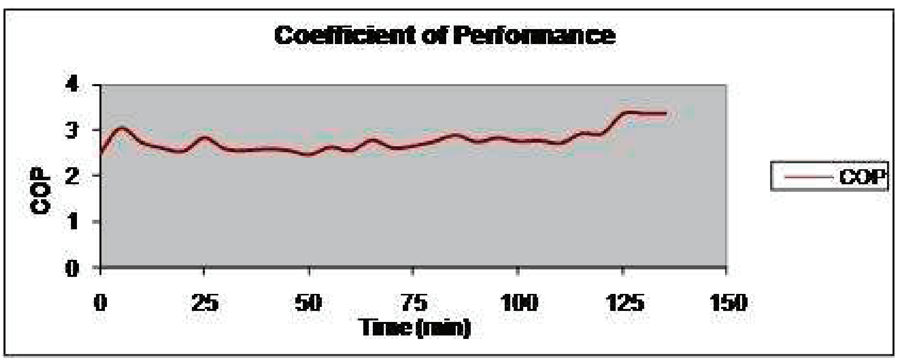

Figure 4.5

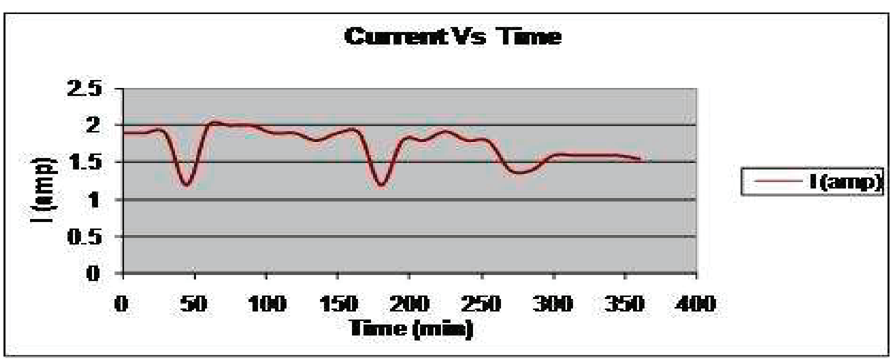

Figure 4.6

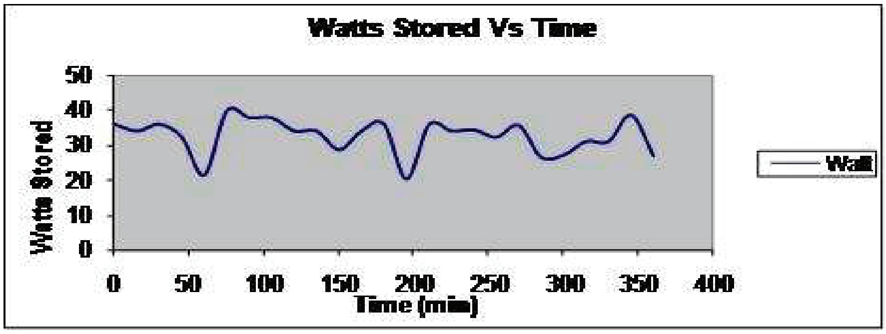

Figure 4.7

5. Economic Analysis

For Economic analysis of solar refrigerator following electricity tariff rates according to the consumer designated by MSEB were considered (as in effect during May-2007).

Consumer	Demand		Tariff Rates (Rs) (per unit)
	Units	**Charges (Rs)**	
Domestic	0 – 100 101 – 300 301 above	40 per month 100 per month 100 per 10KVA	1.90 + Fuel Charges 3.40+ Fuel Charges (0.40) 4.50+ Fuel Charges
Commercial	0 – 100 101–200 201above	150 per month 150 per month 150 per KVA	2.90+ Fuel charges 3.79+ Fuel charges 4.90+ Fuel charges (0.80)
Industrial	0-100	200 per KVA	9.70+ Fuel charges (0.50)

Consumption of electricity (in watts) = Wattage consumed * Operating hours

It is found that the compressor requires **276VA** continuously for performing its function. Taking into consideration the time for which solar radiation is available (typically 7 hours)

Energy consumed by refrigerator = 1932 watts (1.932 units)
Energy consumed in an year = 708.180 units

Cost of electricity for refrigeration = units consumed *(tariff rate + fuel charge) + fixed demand charges

In domestic area = Rs.3891.08 per year (fixed demand charge = Rs. 100 per month)
In Commercial area = Rs.5836.63 per year (fixed demand charge = Rs. 150 per month)
In Industrial area = Rs 7223.44 per year

The total cost of the solar refrigerator is Rs. 49170.00. Thus, the payback periods for different operating sectors are as summarized below

In domestic area = 12.64 years
In Commercial area = 8.42 years
In Industrial area = 6.81 years

6. Conclusion

Solar refrigeration system is the need of future. It is not too far that the world will face the scarcity of energy resources to satisfy the need of energy as well as the need of refrigeration. This demands an efficient and effective use of alternative sources of energy and directed efforts towards their optimum utilization. One of the most promising resources of renewable energy is solar energy, which is available in ample amount at no cost.

The experimental analysis of the prototype setup developed by us suggests that the system performs well at the ambient average temperature of 20-44°C. This approach to refrigeration is a viable solution for the commercial as well as industrial use but is a costly for domestic use.

7. Nomenclature

A	Area of surface (m^2)
C_p	Specific heat (kJ/kg-K)
COP	Coefficient of performance
G_r	Grashof's number
g	The gravitational acceleration (N/m^2)
h_i	Heat transfer coefficient of the inside air (W/m^2K)
h_o	Heat transfer coefficient of the outside air (W/m^2K)
h_x	Heat transfer coefficient of the air (W/m^2K)
K	Thermal conductivity of air (W/mK)
K_{ms}	Thermal conductivity of steel plate (W/mK)
K_{ins}	Thermal conductivity of insulation (W/mK)
L	Length of flat surface (m)
L_{ms}	Thickness of steel plate (m)
L_{ins}	Thickness of insulation (m)
N_u	Nusselt number
N_m	Mean Nusselt number
P	Ambient pressure (bar)
P_c	Condenser pressure (psi)
P_e	Evaporator pressure (psi)
P_r	Prandlt number
Q	Heat flow rate (W)
Q_h	Heat flow rate through horizontal surface (W)
Q_t	Total heat flow rate (W)
Q_v	Heat flow rate through vertical surface (W)
R	Thermal resistance (K/W)
R_a	Rayliegh number
T_c	Condenser temperature (^{0}C)
T_{ci}	Condenser inlet temperature (^{0}C)
T_{co}	Condenser outlet temperature (^{0}C)
T_e	Evaporator temperature (^{0}C)
T_{ei}	Evaporator inlet temperature (^{0}C)
T_{eo}	Evaporator outlet temperature (^{0}C)
T_i	Inside Temperature (^{0}C)
T_o	Temperature of ambient air (^{0}C)

T_s Surface temperature (^{0}C)

T_w Wall temperature (^{0}C)

U Overall heat transfer coefficient (W/m^{2}K)

β Biot number

μ Dynamic viscosity (Ns/m^2)

υ Kinematic viscosity (Ns-m/kg)

ΔT Temperature difference (^{0}C)

δ_t Thermal boundary layer thickness (m)

ρ Density of air (kg/m^3)

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Acknowledgements

The authors would like to thank the management and the staff of RAC laboratory at G. H. Raisoni College of Engineering, Nagpur for their support and assistance. The acknowledgements are also due to the management and staff at Kavikulguru Institute of Technology and Science, Ramtek for their constructive and encouraging comments.