EXPERIMENTAL INVESTIGATION OF POSSIBLE USE OF HDPE AS THERMAL STORAGE MATERIAL IN THERMAL STORAGE TYPE SOLAR COOKERS

Kavendra A. Thakare [1], Honeykumar G. Vishwakarma[2], A. G. Bhave[3]

[1]*Student, M.E. Mechanical (Energy Engineering), K. J. Somaiya College of Engineering, Vidyavihar, Mumbai-400077, India. Email-ID: kaven.thakare@gmail.com.*
[2]*Research Intern, Renewable Energy Lab, K. J. Somaiya College of Engineering, Vidyavihar, Mumbai-400077, India. Email-ID: honeykumar.v@gmail.com.*
[3]*Professor, Department ofMechanical engineering, K. J. Somaiya College of Engineering, Vidyavihar, Mumbai-400077, India. Email-ID:agbhave@gmail.com.*

Abstract

Many Phase Change Materials (PCMs) have been investigated by researchers. They reported limitations of PCMs for use in the thermal storage systems, some of them are: high volumetric change in the PCM while undergoing phase change and low thermal conductivity of the PCMs. Literature survey shows that High Density Polyethylene (HDPE) has relevant thermal properties and can be used as PCM. To investigate the possible use of HDPE in the thermal storage type solar cookers. The simple thermal storage device cum cooking device was designed with two stainless steel utensils easily available in the market. Use of HDPE as the PCM in the thermal storage will eliminate the problem of volumetric change as it has low volume change property during phase transition. To eliminate problem of low thermal conductivity rectangular brass fins were used in the design. Bottom of smaller stainless steel vessel (cooking cavity) was brazed with rectangular brass fins in radial manner with roughly equal angular spacing. HDPE was filled in the void space between cooking cavity with fins and outer stainless steel vessel. The device was then tested for heating, cooling and cooking. The results obtained and conclusions drawn from the experimentation are enlisted in this paper.

KeyWords: High Density Polyethylene (HDPE), thermal conductivity, latent heat, thermal storage, solar cooker.

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1. INTRODUCTION

Polyethylene is a widely used plastic material. It has major share in the plastic market. Due to its corrosion resistant property and durability, it has wide range of applications such as house hold items, packaging, insulation, net ropes, pipes and conduits. It is also used in medical applications as a material to make artificial joints [1].

Polyethylene is a thermoplastic therefore can be reprocessed various times in the temperature range of 150°C-250°C [2] hence widely used in moulding applications. It is easily and abundantly available in low cost.

Polyethylene is categorized into two major categories on the account of density as follows:
   a) Low density polyethylene (LDPE);
   b) High density polyethylene (HDPE).

Sometimes polyethylene with intermediate density is called as medium density polyethylene (MDPE). Different polyethylenes have different processing temperature according to their type. DSC characteristics of polyethylene with different densities [3] are as shown in the Fig-1 and 2.
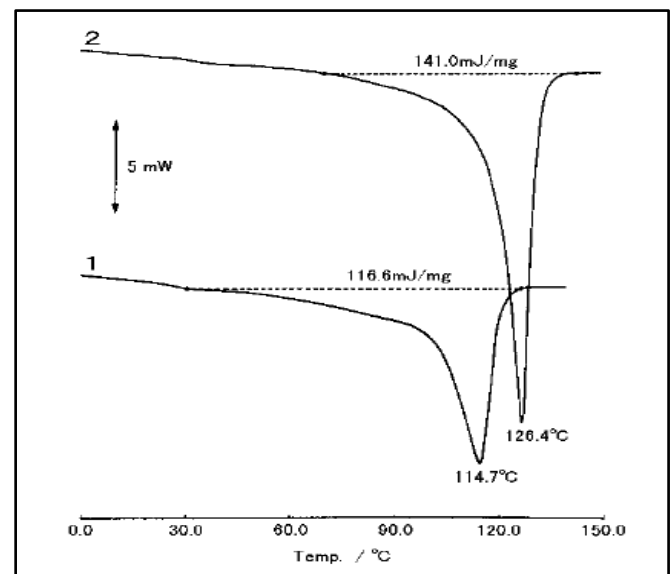
Fig-1: DSC curves of LDPE with density 1) 0.922 g/cm^3 and 2) 0.934 g/cm^3.
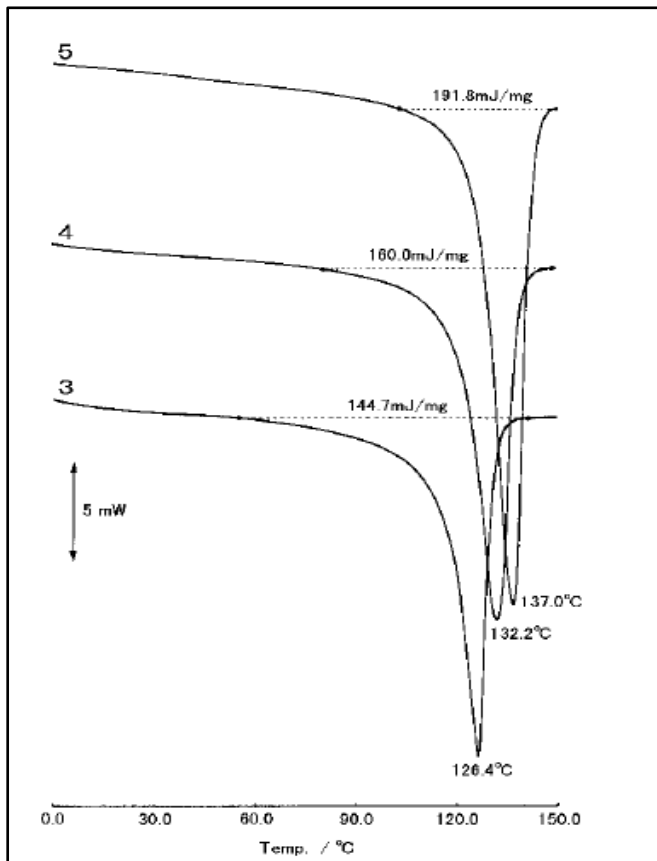
Fig-2:DSC curve for MDPE and HDPE with density 3)0.935 g/cm^3; 4)0.944 g/cm^3 and 5)0.958g/cm^3.

These characteristics show that polyethylene however loses its properties at temperature above 110°C and become soft also flow at higher temperature thus making it unsuitable for high temperature applications. For high temperature applications polyethylene is crosslinked by various methods which improves its thermal properties [3].

The softening of polyethylene in the range of 110°C to 140°C may seem unsuitable for its various applications but it makes polyethylene suitable for latent type thermal storage material in that temperature range as it absorbs some amount of heat during this phase transition period.

The latent type thermal storage materials are also known as the Phase Change Materials (PCM) as they undergo phase change during storage of thermal energy. PCMs have various applications such as solar thermal storage, in building heating and cooling applications, in preservation of food materials, in space applications and many more. Number of PCMs are available with wide range of Phase transition temperatures. Out of those PCMs having Phase transition temperature around 110°C with appropriate latent heat of phase transition can be preferred to use in solar thermal storage in solar cookers for the evening cooking or off sunshine hours cooking [4].

Polyethylene has its phase transition temperature in the range of 110°C-140°C which varies with the variation in the density and have sufficient amount of latent heat of fusion thus we decided to investigate its use as thermal storage material in the solar cooker either box type or concentrating type.
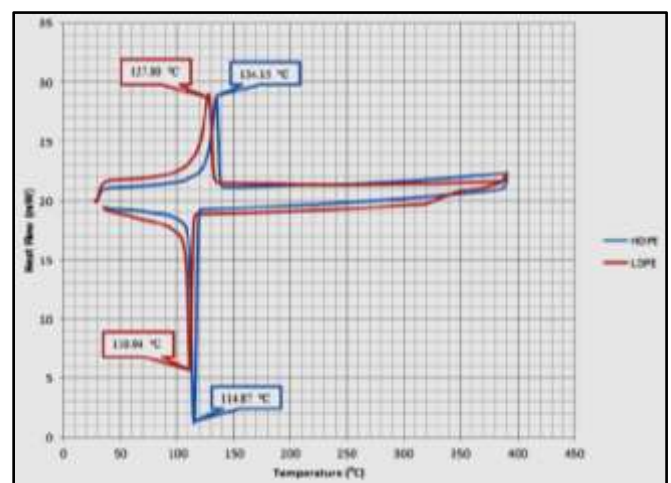
1.1 Properties of HDPE

DSC curve for melting and crystallization of HDPE [5] are shown in following Fig-3.
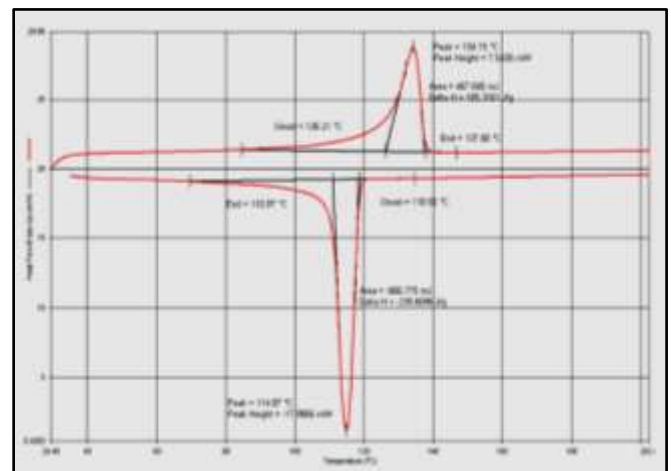
Fig-3: DSC curve for melting and crystallization of HDPE.

From the DSC curve it can be observed that melting temperature of HDPE is around 134°C while the crystallization temperature is noted to be 115°C.

Fig-4 shows the comparison of DSC curves of LDPE and HDPE [5].

Fig-4: DSC curves for LDPE and HDPE.

Thermophysical properties of HDPE are given in the Table 1.

Table-1: Thermophysical properties of HDPE.

High Density Polyethylene (HDPE) [3][5][6].	
Density	940 kg/m^3.
Melting Point	130.8 °C.
Temperature of crystallization	111.9 °C.
Latent heat of fusion	178.6 kJ/kg.
Thermal conductivity	0.44 W/m.°C. at °C.
Specific heat (solid)	1.9 kJ/kg. °C.
Crystallinity	60%

1.2 Solar Cookers with thermal storage

Solar cookers are generally classified as the box type, panel type and concentrating type. But this classification does not give the idea about storage type solar cookers. The Solar cookers can also be broadly categorized as solar cookers (i) with thermal storage and (ii) without thermal storage as discussed by Muthusivagami et al [7].

Many researchers have developed the solar cookers with the thermal storage facility. The thermal storage improves the performance and reliability of the solar cookers by making off-sunshine hours cooking possible. Various PCMs have been used by the various developers. These PCMs have various limitations, but volumetric expansion and poor heat transfer characteristics [4] are the limitations associated with the design of containment. Because of these problems, the design of containment of the PCM and design of thermal storage becomes complicated. The possible solutions to the aforementioned problems are the shape stabilization of PCMs and heat transfer enhancement to and from PCMs. Since HDPE has comparatively low volumetric expansion on heating, it is being used for making of shape stabilized PCMs [1][8]. The problem of low thermal conductivity can be overcome by the use of any heat transfer enhancement technique in the containment design.

2. Literature Review

In 1984 Abe et al [8] from Japan found HDPE as suitable PCM in the Latent heat type thermal storage around 120°C. Later they used form stable HDPE, presently known as cross linked HDPE, as thermal storage material in the direct contact heat exchanger with ethylene glycol and silicone oil as heat transfer fluid. They reported problem of deformation of HDPE even though it was form stabilized.

In the 1996-97 Nandwani et al [9] investigated the use of HDPE as thermal storage material in the box type solar cooker in Germany. They successfully obtained the HDPE slab temperatures around 132°C and found performance of the solar cooker with HDPE slab better than solar cooker without HDPE slab.

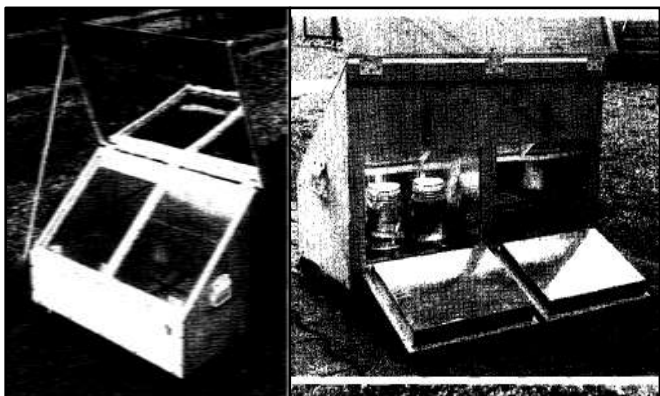Fig -5 shows the images of the box type solar cooker used in the experimentation.

Fig -5: Box type solar cooker used by Nandwani et al [9].

In many cases the PCMs have to be encapsulated to increase its lifespan and prevent direct contact with heat transfer fluid. HDPE is used as the base materail for encapsulation in case of paraffin waxes and 1:1 eutectic mixture of Ammonium alum and ammonium nitrate [11]. The blends made from HDPE and parafin wax can also be used as PCM materials [6]. HDPE has its use in the making of the composite and Shape stabilised PCMs[8][10-13].

HDPE itself can also be used as PCM in the solar thermal storages with operating range 110°C-140°C. The study by Nandwani et al. shows that HDPE can be used as box type solar cookers as thermal storage material, also HDPE can be used as storage medium in the concentrating type solar cookers where temperature around 150°C are easily achievable.

3. Thermal Storage cum cooking Device

From the properties of HDPE and literature review, it is clear that HDPE can be used as PCM in the thermal storage systems. So we decided to investigate the possible use of HDPE in the storage type solar cookers. Though HDPE has promising phase transition temperature (130.8°C) and latent heat storage capacity (178.6 kJ/kg), it has low thermal conductivity (0.44 W/m.°C) too. It becomes viscous when undergoes phase transition thus the conduction will be the prominent mode of heat transfer. Hence to make the use of HDPE in thermal storage one needs to enhance heat transfer to and from the HDPE. For that purpose fins were used in the present experimentation on the thermal storage with HDPE.

To investigate the use of HDPE in the solar cooker with thermal storage facility, we designed the thermal storage device on a smaller scale with two stainless steel utensils, one having bigger diameter and height than the second. Rectangular brass fins were brazed to the bottom of the smaller stainless steel vessel (i.e. cooking cavity) in radial manner with roughly equal angular spacing. Fins enhance the heat transfer to and from the HDPE in heat collection period and heat retrieval period respectively.

The Fig-6 shows the constructional details of the device.
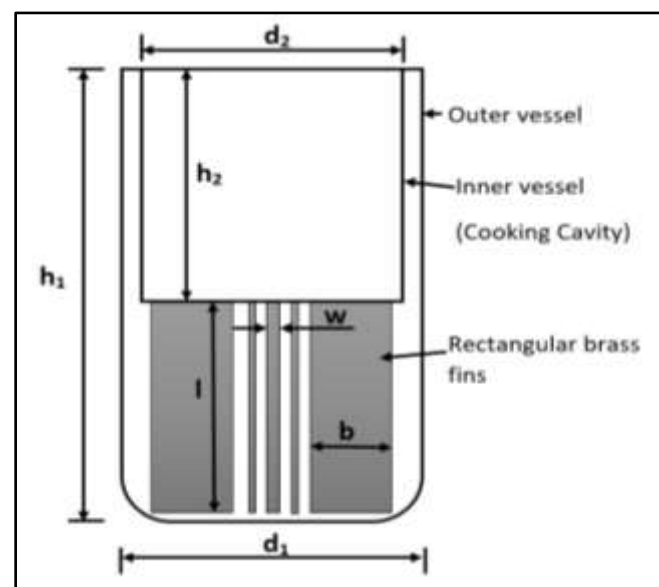
d_1	6.5 cm	d_2	6 cm
h_1	9 cm	h_2	4.5 cm
l	4.5 cm	b	2 cm
w	0.5 mm	n	8 fins

Fig -6: Constructional details of thermal storage device.

Fig -7: Images of Assembly of thermal storage device.

Fig -8: Insulation pot with glasswool insulation.

4. Experimentation and Results

115gm of HDPE was used in the device to store heat and a hot air oven was used to simulate solar heating of the device. As the properties of available HDPE were unknown, for calculations, properties were assumed to be same as mentioned in the Table-1. The HDPE was heated to the melting point in the bigger utensil (shown as outer vessel in the Fig-7) then the smaller vessel was pressed to fit against the molten HDPE. A thermocouple was inserted into the HDPE such that it can give the HDPE temperature from the center of the device. The final assembly is as shown in Fig-7.

4.1 Heating and Cooling Test

The heating (Melting of HDPE) and cooling (Crystallization of HDPE) tests were carried out on the device. Heating test comprised of preheating of the hot air oven till the set temperature and then heating of device in the oven till the HDPE temperature reaches around 150°C. After that the device was taken out from the oven and kept inside the insulation pot and allowed to cool with controlled heat loss to the surrounding.

The observation tables of the heating and cooling test of the device are illustrated in the Table-2 and 3 with the corresponding graphs i.e. Graph 1 and 2 respectively.

The sensible and latent heating phases of the HDPE can be observed from the Graph 1. While in Graph 2 the low slope of the temperature curve between 125°C to 110°C indicates the release of latent heat from the HDPE.

Table-2: Temperature readings of Heating Test 1.

Time (min)	T_{HDPE} (°C)	T_{oven} (°C)	T_{set} (°C)
0	32	160	160
10	76	160	160
20	106	160	160
30	120	160	160
35	124	160	160
40	126	160	160
45	129	160	160
50	131	160	160
55	134	160	160
65	143	160	160
70	148	160	160
75	152	160	160
77	154	160	160

Table-3: Temperature readings of Cooling Test.

Time (min)	T_{HDPE} (°C)
0	154
2	149
4	143
6	136
8	130
10	125
15	123
18	123
20	122
22	121
24	120
26	118
28	117
30	116
32	114
34	112
36	110
38	107
40	105
42	103
44	100
46	98
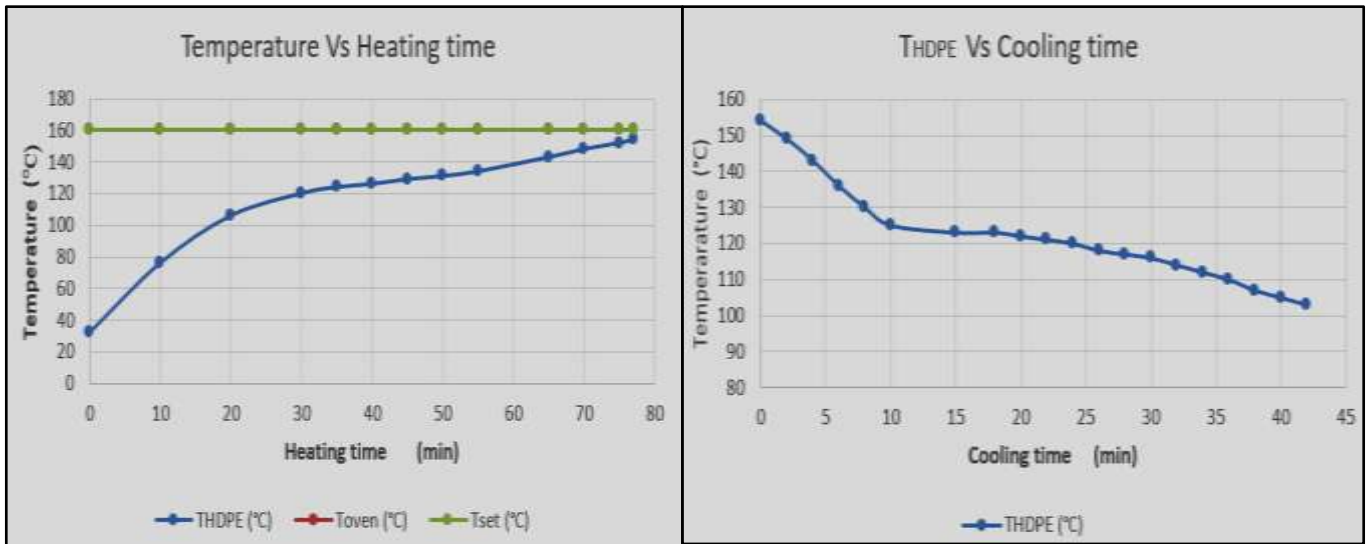
Graph 1: Temperature Vs Heating time 1.   **Graph 2**: Temperature Vs Cooling time.

4.2 Cooking Test

For cooking test the device was heated in the oven in similar manner to that of the heating and cooling test except that the preheating of oven was not done. HDPE was heated till its temperature crosses the melting point. After that device was taken out from the oven and kept in the insulation pot to minimize the heat loss to the surrounding. 15 gm of rice with 30ml of water was put in the cooking cavity provided on the device. The cooking cavity was covered with a lid to avoid heat losses to the surrounding while cooking and then the food was allowed to cook. The HDPE temperature during cooking test was recorded at regular intervals. The cooking time for given amount of food, was observed to be around 25 minutes. Afterwards the weight of cooked rice was recorded for further calculations. The observation table for heating and cooking test carried out on the device are presented in the Table-4 and 5 with the corresponding graphs i.e. Graph 3 and 4 respectively. From the Graph 3, the sensible and latent heating phase of the HDPE can be observed. While the low slope of the temperature curve between 115°C to 100°C during cooking indicated the release of latent heat from the HDPE.
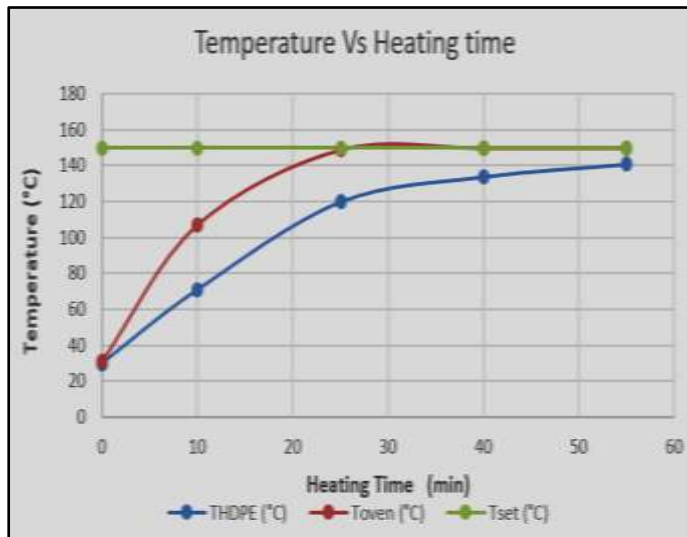
Fig-9 shows the image of cooked rice in the cooking cavity with the device kept inside the insulation pot.

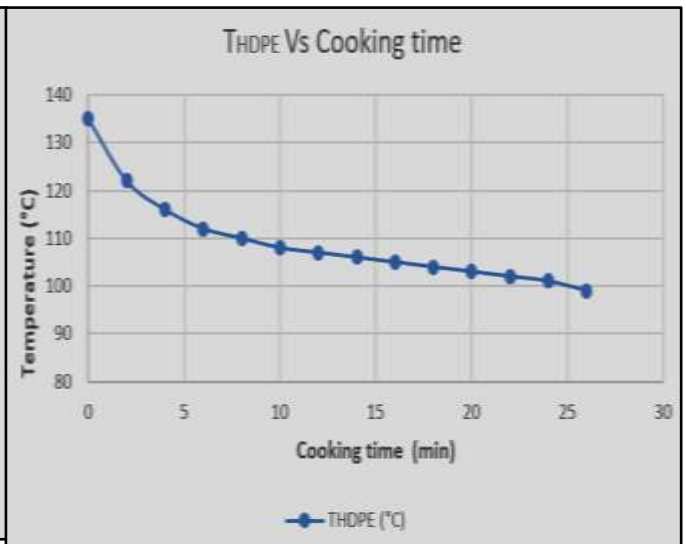**Table-5**: Temperature readings of Cooking Test.

Time (min)	T_{HDPE} (°C)
0	135
2	122
4	116
6	112
8	110
10	108
12	107
14	106
16	105
18	104
20	103
22	102
24	101
26	99

Table-4: Temperature readings of Heating Test 2.

Time (min)	T_{HDPE} (°C)	T_{oven} (°C)	T_{set} (°C)
0	30	30.9	150
10	71	107	150
25	120	149	150
40	134	150	150
55	141	150	150

Graph 3: Temperature Vs Heating time 2.

Graph 4: Temperature Vs Cooking time.

Fig-9:Image of cooked rice in the cooking cavity.

Few more heating and cooking tests were carried out on the device and similar results were obtained.

5.Calculations

Table-6 enlists the data used for calculations.

Table-6: Data used for calculations.

m_{sc}	20 gm	C_{psc}	500 J/kg.°C
m_{fin}	50 gm	C_{pfin}	380 J/kg.°C
m_{Hs}	115 gm	$C_{pHs} = C_{pHl}$	1.9 kJ/kg.°C
H_{L_H}	180 kJ/kg	T_f	141°C
T_m	131°C	T_a	30°C
m_r	15 gm	C_{pr}	1.716 kJ/kg.°C
m_w	30 gm	C_{pw}	4.187 kJ/kg.°C
m_{we}	7 gm	H_{L_w}	2256 kJ/kg

5.1 Energy balance calculations:

Total thermal Energy stored throughout the heating test neglecting energy stored in outer vessel is given as:

Total Thermal Energy Stored

$$= m_{sc} C_{psc} [T_f - T_a]_{sc}$$
$$+ m_{fin} C_{pfin} [T_f - T_a]_{fin}$$
$$+ m_{Hs} C_{pHs} [T_m - T_a]_{Hs} + m_{Hs} H_{L_H}$$
$$+ m_{Hl} C_{pHl} [T_f - T_m]_{Hl} \dots \dots (1)$$

$$\therefore Q_{stored} = 48.173 \text{ kJ}.$$

Similarly thermal energy stored above 100°C in the HDPE and cooking cavity which is useful for boiling type of cooking is given as:

Total Thermal Energy Stored above 100°C

$$= m_{sc} C_{psc} [T_f - 100]_{sc}$$
$$+ m_{fin} C_{pfin} [T_f - 100]_{fin}$$
$$+ m_{Hs} C_{pHs} [T_m - 100]_{Hs} + m_{Hs} H_{L_H}$$
$$+ m_{Hl} C_{pHl} [T_f - T_m]_{Hl} \dots \dots (2)$$

$$\therefore Q_{stored \ >100°C} = 30.848 \text{ kJ}.$$

Energy required to cook 15g of rice with 30 ml of water is given as: (mass of cooked rice = 43 gm)

Energy required to cook 15g rice with 30 ml of water

$$= m_r C_{pr} [100 - T_a]_r$$
$$+ m_w C_{pw} [100 - T_a]_w$$
$$+ m_{we} H_{L_w} \dots \dots (3)$$

$$\therefore Q_{cooking} = 26.387 \text{ kJ}.$$

5.2 Efficiency Calculations:

Cooking efficiency with respect to total thermal energy stored is given as:

$$\eta_{stored} = \frac{Q_{cooking}}{Q_{stored}} \qquad \ldots \ldots (4)$$

$$\therefore \eta_{stored} = \frac{26.387}{48.173} = 0.5478 = 55.78\% \quad .$$

Cooking efficiency with respect to thermal energy stored above 100℃ is given as:

$$\eta_{stored\ >100℃} = \frac{Q_{cooking}}{Q_{stored\ >100℃}} \qquad \ldots \ldots (5)$$

$$\therefore \eta_{stored\ >100℃} = \frac{26.387}{30.848} = 0.8554 = 85.54\% \quad .$$

6. CONCLUSIONS

Following conclusions are drawn from the experimentation carried on the HDPE.

1. Graphs for heating and cooling test show the similar temperature trends to the ideal heating and cooling curves in case of Latent heat stored and released.

2. Temperature trends in the graphs show that the latent heat was stored and released near respective melting and crystallization temperatures of HDPE.

3. Energy balance and efficiency calculations show that the device has good thermal characteristics.

4. The higher values of efficiencies may be due to assumed properties of HDPE but seem to be attractive.

5. The concept of thermal storage device was proved.

6. The overall results show that the HDPE can be used as PCM in storage type solar cookers.

Nomenclature

PCM	Phase Change Material
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
DSC	Differential Scanning Calorimetry
m	Mass (kg)
C_p	Specific heat (kJ/kg.℃)
T	Temperature (℃)
H_L	Latent heat of Phase transition (kJ/kg)
Q	Quantity of heat (kJ)
H	Efficiency
n	Number of fins

Suffix

sc	Stainless steel cooking cavity
fin	Brass fins
Hs	HDPE solid
Hl	HDPE liquid
r	Rice
w	Water
We	Water evaporated
F	Final
a	Ambient
m	Melting
stored	Total stored
stored >100℃	Stored above 100℃
cooking	For cooking
oven	Oven
set	Set temperature of oven

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BIOGRAPHIES

Kavendra A. Thakare received the B. Tech. degree in Marine Engineering from Maharashtra Academy of Naval Education and Training, Pune in 2010. He is now pursuing M.E. in Energy Engineering from K. J. Somaiya College of Engineering, Mumbai University.
Email-ID: **kaven.thakare@gmail.com**

Honeykumar G. Vishwakarma completed his Bachelor of Engineering in Mechanical Engineering from K. J. Somaiya College of Engineering, Mumbai. Currently doing internship in Renewable Energy Lab, K.J.Somaiya College of Engineering.
Email-ID: **honeykumar.v@gmail.com**

Dr. A.G. Bhave received the degree of Docteur - Ingenieur in Thermique Industrielle, in the area of solar thermal energy, from Universite Paris XII in 1985. He has worked in the renewable energy area since, and is working as a professor in the Mechanical Engineering Department of K. J. Somaiya College of Engineering, Mumbai since 2009.
Email-ID: **agbhave@gmail.com**