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ABSTRACT

The main energy source of developing countries for cooking comes from biomass. Like most developing countries, Ethiopia is also dependent on using traditional fuels. More than 98% of its household energy comes from biomass and less than 2% from electricity and petroleum collectively. The biomass energy is mainly used to bake the country’s common food type called “Injera” and its stew. During traditional biomass, the injera baking process kitchen environment is highly polluted with soot and smoke that affect the health of household inhabitants. In addition to that, it will highly contribute to climate change. The source for fuel wood is forest and due to deforestation desertification and soil degradation will happen. Another alternative source for Injera baking is electricity but it has high fluctuation and not available in rural areas. In order to overcome those problems this paper propose solar thermal injera baking method integrated with heat storage material. Phase change material was integrated into the system to allow night-time baking. Nitrite salt (40%KNO3-60%NaNO3) was used as energy storage material due to its highest melting temperature (222°C). Nanofluid used was Cu/shell Thermia oil B with a volume concentration of 4% of nanoparticle. Thermo-physical property for nanofluid was calculated using theoretical models obtained from the literature. The use of nanofluid enhance thermal performance of the system compared with conventional fluid used for injera baking method (shellthermia oil B and steam). CFD simulation using ANSYS fluent was done to determine the charging time for PCM using nanofluid and shellthermia oil B as heat transfer fluid. Simulations show the use of nanofluid reduce charging time for PCM by 30.6%.
INTRODUCTION

The main energy source of developing countries for cooking application comes from biomass. Studies show about 800 million people who are dependent on this form of energy are exposed to death and critical health problems. This is worse in the Sub-Saharan Africa (SSA) region where there is high biomass energy demand with a steady population growth. It accounts for 70 % to 90 % of primary energy for most SSA countries. The energy estimation of 2030 shows one billion Africans will depend on traditional biomass and half a million will die from its impact. Like most developing countries, Ethiopia is also dependent on using traditional fuels [1]. More than 98% of its household energy comes from biomass and less than 2% from electricity and petroleum collectively. The biomass energy is mainly used to bake the country’s common food type called “Injera” and its stew. Injera is commonly prepared from “Teff” (Eragrostis tef), and is consumed two to three times per day by most household. Generally, more than 50% of the biomass fuel is used to bake this food item. The kitchen used to bake Injera is highly polluted with smoke, soot, and products of incomplete combustion. The use of biomass fuel in a traditional stove has been affecting the health and school time of millions of women and children. It also puts pressure on the country’s forest coverage leading to erosion and land degradation. Injera is spongy flat bread with a distinctive test and texture. It is predominately eaten as staple food item in Ethiopia and some parts of East Africa. It is similar to an Indian Chapatti with small bubbly structures or eyes on top. In most households of Ethiopia, the energy demand for baking Injera is largely met with biomass such as: fuel wood, agricultural residue and dung cakes. In addition to the off-focus solar thermal application, they discussed the integration of solar thermal with heat storage for sustainable future use [2]. The prototype for direct steam-based baking was developed and tested in Mekelle University (Ethiopia) and Phase change material based heat storage prototype was developed and tested at NTNU. Both experiments showed the possibility of solar energy for Injera baking and its sustainability by including latent heat storage.

MATERIALS AND METHODS

Charging and discharging of phase change material heat storage using steam as working fluid. PCM they used to be nitrite salt which was a mixture of 60% NaNO3 and 40% KNO3. The storage has charged on successive days using the advantage of materials heat retention ability by using energy from the sun with circulating steam temperature of 250°C. Also they charged the material with an artificial heater with the surface temperature maintained at 450°C and obtained charging time of 8 hours. Different types of high-temperature thermal storage materials. The range of temperature studied was between 180 and 250°C. A comparison between the best sensible heat materials (iron, carbon) and melting materials (nitrate salts, tin) is realized to conclude on the relevance of latent heat storage system compare to sensible heat based ones. For latent heat storage, Potassium-Sodium nitrate salts (KNO3-NaNO3) and tin were used with the melting temperature of 220°C and 220°C consecutively. For the sensible heat materials, two different materials will be studied: iron, which has been chosen because of its high volumetric and slightly increasing sensible heat regarding the temperature and graphite, because of its significantly increasing sensible heat regarding the range of temperature. Finally, they obtained that Total heating time is much shorter for the latent heat-based system and by comparison of the heat capacities the latent-heat based systems are more effective than the sensible-heat. A thermal storage can significantly increase the performance and competitiveness of a solar installation. Solar irradiation is intermittent and irregular, so storage can correct this variation to optimize the use of the energy collected. There are three methods for storing thermal energy (Figure 1).

Figure 1: Methods for storing thermal energy.
Sensible heat storage is method of storing energy without causing a phase change on material. Energy stored due to increase of temperature on the material. Amount of energy stored depends of specific heat, temperature change and the amount of material. Latent heat thermal energy storage (LHS) involves heating material until it experiences a phase change, which can be from solid to liquid or from liquid to gas; when the material reaches its phase change temperature it absorbs a large amount of heat to carry out the transformation, known as the latent heat of fusion or vaporization depending on the case, and in this manner the energy is stored.

RESULTS AND DISCUSSION

Selection of phase change material for the energy storage depends on the variety of properties.

- Phase change temperature of material it should be near to operating temperature
- Latent heat of material it should be high to minimize volume of size
- High specific heat to store additional heat
- High thermal conductivity on both state
- High density, small volume changes at both solid and liquid phase
- Should not be toxic, flammable, or explosive

Some of nitrite salts that are used as PCM material were presented below and the best PCM for the proposed system will be selected (Table 1).

Table 1: Properties of PCM.

<table>
<thead>
<tr>
<th>PCM</th>
<th>Melting temperature°C</th>
<th>Melting enthalpy(J/g)</th>
<th>Thermal conductivity(w/m.k)</th>
<th>Specific heat capacity (J/g,k)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaNO2</td>
<td>270</td>
<td>200</td>
<td>0.96</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>NaNO3</td>
<td>306</td>
<td>175</td>
<td>0.59</td>
<td>1.78</td>
<td>1.8</td>
</tr>
<tr>
<td>KNO3</td>
<td>337</td>
<td>100</td>
<td>0.4</td>
<td>1.43</td>
<td>1.46</td>
</tr>
<tr>
<td>60% NaNO3 - 40% KNO3</td>
<td>222</td>
<td>100</td>
<td>0.5</td>
<td>1.42</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Thermophysical properties of nanofluid by using theoretical models. They improved thermophysical properties of conventional fluids by suspending nanoparticles (Figure 2).

Figure 2: Theoretical models to calculate thermophysical properties of the nanofluid.

<table>
<thead>
<tr>
<th>No</th>
<th>Property of nanofluid</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific heat (KJ/kg.k)</td>
<td>[ c_{nf} = (1 - \phi)\rho_f C_f + \phi \rho_p C_p ]</td>
</tr>
<tr>
<td>2</td>
<td>Density (kg/m3)</td>
<td>[ \rho_{nf} = (1 - \phi)\rho_f + \phi \rho_p ]</td>
</tr>
<tr>
<td>3</td>
<td>Prandtl number</td>
<td>[ Pr = \frac{\nu_{nf}}{\alpha_{nf}} ]</td>
</tr>
<tr>
<td>4</td>
<td>Dynamic viscosity</td>
<td>[ \mu_{nf} = \frac{\mu_{bf}}{(1 - \phi)^{2.5}} ]</td>
</tr>
<tr>
<td>5</td>
<td>Thermal diffusivity</td>
<td>[ \beta_{nf} = \frac{(1 - \phi)\beta_f^2 + \phi \beta_p^2}{\rho_{nf}} ]</td>
</tr>
</tbody>
</table>

Where \( \rho_{nf} \)=density of nanofluid, \( \phi \)=Nanoparticle percent concentration, \( \rho_f \)=density of base fluid, \( \rho_p \)=density of nanoparticle, \( C_{nf} \)=heat capacity of nanofluid \( C_f \) heat capacity of base fluid \( C_p \) heat capacity of nanoparticle. Previously shell Therma oil B and steam used as heat transfer fluid. The thermal conductivity of the oil is low due to this heat transfer rate from the fluid to the storage is low. This increases charging time for injera
storage. For the case of steam as heat transfer fluid the pressure on the piping system would develop up to 40 bar and due to condensation of the steam on the pipe corrosion could happen on the wall of the pipes. This could reduce the life of the system. Cu/shell Thermia oil B nanofluid (4% concentration of copper) used as heat transfer fluid for this system. Copper has high thermal conductivity when compared with another nanoparticle, this will enhance the property of the nanofluid. Shell Thermia Oil B is used as a base fluid.

System description

The proposed system contains parabolic trough collector for heat collection, valves to control flow direction, pumps to drive fluids, phase change materials to store energy for night time baking purposes, temporary oil storage gallery below the pan to control the fluctuation of the temperature on the surface of the pan during baking, pipes for the flow of the fluids through the system, and insulations. When radiation from the sun reaches the surface of the collector the fluid inside the absorber starts to absorb heat. Pump I is used to driving fluid from the oil storage to the absorber and the fluid starts to flow through the absorber by absorbing amount of heat from the collector the system contains three loops, loop I is used to charging PCM, loop II is used to discharge PCM (night time cooking) and loop III, is used for day time baking of injera. Pump II is used to drive oil from the oil gallery to the storage and to discharging of PCM (Figure 3).

Numerical modeling

Solidification and melting model on the ANSYS fluent 16.0 is used to model and simulate the melting of PCM. The material was simulated for two different working fluid (nanofluid and Thermia oil B) to compare its fully charging time required. Main parameters that used on this model is liquid fraction (fraction of cell volume which is in liquid form) and mushy zone (which the value of Liquid fraction changes from 0 to 1). Continuity, mass and energy equations applied to solve the problem. Governing equations used were

Energy equation

$$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} \cdot H) = \nabla \cdot (k \vec{v} \cdot T) + S$$

(1)

The source term, S contains contributions from convection, latent heat transfers due to phase change and any other volumetric heat sources. Where, H is the enthalpy, \(\rho\) is the density, \(\vec{v}\) is the velocity of fluid and S is the source term. The enthalpy H is calculated as the sum of sensible and latent heat.
Boundary conditions used for the simulation

Boundary conditions are the set of conditions specified for the behavior of the solution to a set of differential equations at the boundary of its domain. Boundary conditions are important in determining the mathematical solutions to many physical problems. Governing equation used were energy, momentum and continuity equations. Boundary conditions used (Table 2):

- No slip conditions, (At fluid wall interface, there must be no slip)
- Inlet temperature of the fluid (260°C)
- Inlet mass flow rate
- Outlet was set to outflow (for unknown flow condition) condition
- Interface between the pipe and PCM face was coupled
- Outer wall of the container is insulated so zero heat flux.

<table>
<thead>
<tr>
<th>Zones</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>Outlet</td>
<td>Outflow</td>
</tr>
<tr>
<td>Outer wall</td>
<td>Wall</td>
</tr>
<tr>
<td>PCM</td>
<td>Interior</td>
</tr>
</tbody>
</table>

Assumptions used:
- Melting process is transient
- Two dimensional analysis
- Thermo physical properties of the HTF and the PCM are constant
- Initial temperature of the system is uniform and the PCM is in the solid phase for melting.
- Inlet temperature and mass flow rate of HTF is constant (Figure 4).
Meshing

Meshing is a method of dividing the flow domain into many elements or subdomains. Equations are solved in those domains (Figure 5).

The presence of good meshing has a significant effect on the rate of convergence, solution accuracy and computation time. So the quality of meshing is checked by performing mesh sensitivity analysis. Steady state analysis was used to check mesh sensitivity for storage (Figure 6 and 7).
Figure 7: Mesh sensitivity analysis results.

<table>
<thead>
<tr>
<th>Mesh size [mm]</th>
<th>PCM temperature (k)</th>
<th>Outlet temperature (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10mm</td>
<td>304.94717</td>
<td>518.5846</td>
</tr>
<tr>
<td>5mm</td>
<td>308.62027</td>
<td>503.26312</td>
</tr>
<tr>
<td>3mm</td>
<td>309.29141</td>
<td>495.73276</td>
</tr>
<tr>
<td>2mm</td>
<td>309.4275</td>
<td>494.34382</td>
</tr>
<tr>
<td>1mm</td>
<td>309.62893</td>
<td>493.09969</td>
</tr>
<tr>
<td>0.5mm</td>
<td>309.8</td>
<td>310.11099</td>
</tr>
</tbody>
</table>

CFD results phase change material for nanofluid and shell Thermia oil as HTF

The simulation for PCM was performed by ANSYS 16.0 (fluent). Models used were Solidification and melting, energy and laminar flow (Figure 8).

Figure 8: Fluid PCM arrangement.

For the PCM heat transfer was by conduction at its solid state and convection at its liquid phase. Liquid fraction for PCM using nanofluid as HTF at different time (Figure 9).

Figure 9: Liquid fraction for PCM using nanofluid at different time.
The liquid fraction contour above shows amount of PCM that melted (liquid fraction) for a given time. PCM material could melt after absorbing enough amount of energy required to melt. At time 0sec or initially the system was at room temperature so, all PCM was at solid state. 30% of PCM material was melted due to addition of heat to the system at time 15,000sec and after 23,000sec 75% of PCM was melted. The PCM was completely at liquid state after 33,3334sec figure d) shows this condition. The representation of liquid fraction versus time was depicted on the graph (Figure 10).

**Figure 10**: a) Mass fraction versus charging time b) temperature versus charging time (using nanofluid).

As heat transfer to the PCM the temperature of the material will increase. Initially the PCM absorber sensible energy so its temperature would increase up to melting point of the material. At the melting point it starts to absorber latent form of energy and its temperature would be nearly at constant value. After finishing this stage, it stares to absorber sensible form on energy due to that inlet temperature is greater than that of melting temperature of material (figure 11 and 12).

To confer the performance of nanofluid with conventional fluid the same simulation was done for PCM material using shell Therma oil B and the results were represented graphically below:

**Figure 11**: a) Mass fraction versus charging time b) temperature versus charging time (using shellthermia oil B).

**Figure 12**: Charging time comparison.
Initially the phase change material was at the ambient temperature. When the inlet fluid with temperature of 255°C pass through the PCM its temperature start to increase. The material has been on solid state until its temperature reach to the melting temperature or absorber enough amount of heat to melt the material. When a material starts to melt, amount of PCM melted was represented by liquid fraction or mass fraction. It absorbs sensible heat up to melting temperature of 222°C and latent heat at its melting point. Inlet temperature was higher than that of melting temperature of the material, so it absorbs additional amount of energy after melting completely. The simulation on this thesis was performed for two fluids, nanofluid and shell Therma oil B.

**DISCUSSION**

The aim of this simulation is to determine the performance of those fluids regards to the time required to charge the material completely [3]. Step by step melting process has been represented by contour for the liquid fraction and temperature for the PCM on the above figures.

Using nanofluid as heat transfer fluid, the PCM material start to melt at 13750 seconds (3hrs and 48 minutes). It would be completely liquid state after 33334seconds (9hrs and 15 minutes) [4]. The maximum temperature from simulation result obtained was 240°C. So, it shows that the material stored additional amount of energy at the sensible range.

Using shell Therma oil B as heat transfer fluid, the PCM material start to melt at 24900 seconds (6hrs and 54 minutes) [5]. It would be completely liquid state after 480004seconds (13hrs and 18 minutes). The maximum temperature from simulation result obtained was 237°C. So, it shows that the material stored additional amount of energy at the sensible range. From the above results using nanofluid as heat transfer fluid enhance the charging time required to melt the PCM material and maximum temperature would be stored.

**CONCLUSION**

Injera baking method in Ethiopia is the most energy-consuming process. Its main energy sources are firewood, animal dungs, and crop residues. Those energy sources have a great effect on the environment and human being items of environmental degradation and room clean air. Due to this problem, this paper proposes solar energy as an alternative energy source for the Injera baking process. The proposed system contains energy storage material that is used for night time baking process. From the CFD modeling and simulation, charging time required for the PCM was obtained. The PCM was fully charged at 9hrs and 15minutes with maximum temperature stored on it was 240°C using nanofluid and it was fully charged at 13 hrs and 18 minutes with maximum temperature stored on it was 237°C for shell Therma oil. The result of this simulation showed that the use of nanofluid reduce charging time (30.6%) of the PCM.

**REFERENCES**