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Design of Solar Thermal Injera Baking System Using Nanofluid as Heat Transfer Fluid

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ABSTRACT

Solar energy is one of the most promising renewable energy sources since it is free, available at all locations, and non-polluting. During the traditional biomass 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. The use of solar energy with nanofluid can enhance the system efficiency and remove all problems mentioned above. On this article solar thermal injera baking system by using nanofluid as heat transfer media is designed. Total amount of energy required for a single baking period is 17,417.16kJ by considering average family size of five and each will consume three injera per day the total amount of injera required per day is 15 injera, for three days 45 injera. From the design process it was observed that the use of nanofluid reduce the size of commoponanats when we compare with other types of conventional fluids. The use of nanofluid for the solar thermal injera baking method reduces the time required for the baking process.

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 Asfafaw et al., (2014). 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. 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 Tesfaye et al.,(2014).

Injera is spongy flat bread with a distinctive test and texture. It is predominantly 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 bio-mass such as: fuel wood, agricultural residue and dung cakes. Whereas, electricity is used in some of urban households Abdulkadir,et al,(2013). Recent energy crises motivated researchers to improve the stove efficiency and its possibility to work with other alternative energies such as biogas and solar. Solar energy is one of the most promising renewable energy sources since it is free, available at all locations, and non-polluting.

This paper will design possibility of the high temperature indoor solar cooking and reduced initial heating up time by using Nano fluid as heat transfer fluid. The enhancement of heating or cooling may create a saving in energy, reduce process time, raise thermal rating and lengthen the working life of equipment. Heat transfer efficiency can also be improved by increasing the thermal conductivity of the working fluid. Commonly used heat transfer fluids such as water, ethylene glycol, and engine oil have relatively low thermal conductivities, when compared to the thermal conductivity of solids. Nano fluid is a new kind of heat transfer medium, containing nanoparticles (1–100 nm) which are uniformly and stably distributed in a base fluid. These distributed nanoparticles, generally a metal or metal oxide greatly enhance the thermal conductivity of the Nano fluid, increases conduction and convection coefficients, allowing for more heat trans.

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment, or to a thermal energy storage tank from which can be drawn for

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use at night and/or cloudy days. There are basically two types of solar collectors: non concentrating or stationary and concentrating. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux.

LITRETURE REVIEW

Injera baking process requires large amount of temperature (180^0-220^0)C Asfafaw et al., (2014). In order to deliver high temperatures with good efficiency a high-performance solar collector is required. Systems with light structures and low-cost technology for process heat applications up to 400^0could be obtained with parabolic through collectors (PTCs). PTCs can effectively produce heat at temperatures between 50^0C and 400^0C Kalogirou et al,.(2004)

Nanofluid are colloidal suspensions of Nanosized solid particles in a liquid. Recently conducted experiments have indicated that Nanofluid tend to have substantially higher thermal conductivity than the base fluids. Among the many advantages of Nano fluids over conventional solid-liquid suspensions, the following are worth mentioning.

> Higher specific surface area

> Higher stability of the colloidal suspension

> Lower pumping power required to achieve the equivalent heat transfer

> Reduced particle clogging compared to conventional colloids

> Higher level of control of the thermodynamics and transport properties by varying the particle material, concentration, size, and shape Bianco et al,.(2015).

Kumar et al. (2018), experimentally studied the effect of Nano fluids and absorber tube geometry on the heat transfer process. They modified absorber tube with copper fins and using (TiO2) Nano fluid with (0.5g and 1 g) concentration. They obtained various results with changing the Nano fluid concentration outlet temperatures are measured and without the addition of Nano fluids outlet temperatures are measured. They described that the outlet temperature increases with increases in Nano fluid concentration and also Fins are used to increases the surface area so that the heat transfer rate increases. Korres et al. (2019) did an investigation of a Nano fluid-based compound parabolic collector under laminar flow condition. The examined Nanofluid is Syltherm 800/CuO with 5% volumetric nanoparticle concentration and the examined temperature range is from 25^0 Cup to 300^0 C. From the results they concluded that the use of Nano fluid-based CPC is most appropriate at higher temperature levels where the thermal efficiency enhancement is higher and also there is exergy efficiency enhancement. The application of Nano fluids increases the flow heat transfer coefficient by 15.53% for the low operating temperatures and up to 17.41% in the high operating temperatures. The mean heat transfer coefficient enhancement is 16.16%. Azari et al.,[2014], studied experimental and Computational Fluid Dynamics (CFD) investigations of the laminar convective heat transfer coefficient of Al2O3/water Nano fluids in a circular tube under uniform and constant heat flux on the wall. Experimental and simulation results showed that the thermal performance of Nano fluids is higher than that of the base fluid and the heat transfer enhancement increases with the particle volume concentration and Reynolds number.

Ketan & Kundan (2016), studied Experimental and CFD Investigation of the Parabolic Shaped Solar Collector Utilizing Nanofluid (CuO-H2O and SiO2-H2O) as a Working Fluid. ANSYS FLUENT 14.5 is used for carrying out CFD investigation. Nano fluids of SiO2-H2O andCuO-H2O of 0.01% volume concentration are used. From their experimental and CFD analysis they obtained Improvement in the efficiency of collector of about 6.68% and 7.64% is obtained using 0.01%vol. conc. SiO2-H2O Nano fluid and 0.01% vol. conc. CuO-H2O Nano fluid, respectively, as compared to H2O at 40LPH while at 80 LPH improvement in efficiency of collector of about 7.15% and 8.42% is obtained using 0.01% vol. conc. SiO2-H2O Nanofluid and 0.01% vol. conc. CuO-H2O Nanofluid, respectively, as compared to H2O.

METHODOLOGY

Methodology includes energy consumption analysis of injera baking method, designing of temporary heat storage tank, sizing of PCM and parabolic trough collector.

Energy consumption analysis of injera baking pan (mittad)

Energy required in baking is defined as the amount of heat required to raise the temperature of batter from ambient to boiling point of water and vaporize portion of water on the batter

Energy utilized on cooking Injera

$Eu=C_{pwater}\,(T_{boil}-T_{room})(m_{batter}-m_{injera})\,h_{vaporization}$ .... (1)

C_{pwater} Specific heat capacity of water =4.187kJ/kg.k. This is due to heat capacity of batter is the same as that of water (batter contains 70% of water and 30% of cereals) Alula et al.,(2013)

T_{boil}=boiling temperature of water is 90.5^0 C

T_{room}=ambient temperature of Jimma which is 19^0 C

$h_{vaporization}$- Heat of vaporization of water hfg=2269.86 kJ/kg

$Eu=0.4kg*4.187kJ/kg.k(90.5-19)k+(0.4kg-0.32kg)2269.86kJ/kg$

Eu=300.78kJ/injera

Taking average family size of five and each will consume three injera per day the total amount of energy utilized will be Amount of injera required per day is15 injera, for three days 45 injera .People use injera daily here but, once baked injera is used for three consecutive days so, the energy consumption of the system is calculated for the amount of injera used for three days. Injera is baked twice per week in general.

Eu=300.78kJ/injera*45 injera=13,500KJ

Energy required for heating up a baking pan

Heating up energy is the amount of energy required to reach the baking temperature of the injera on the surface of the pan (180^0).

$Qh=m_{pan}\ C_{pan}\ (T_{baking}-T_{room})$ 2

Where Qh=heating up energy,

m_{pan}=mass of pan (average mass of pan is 7kg) Melakmu (2013)

C_{pan}=heat capacity of pan =0.9kJ/kg. k

T_{baking}=temperature of the baking surface of the pan 180^0 c

Qh=7kg*0.9kJ/kg.k(180-19)k

Qh=1,014.3KJ

Total amount of energy=Energy utilized +Heating up energy

Qt=Eu+Qh 3

=1,014.3kJ+13,500KJ = 14,514.3kJ

But there are loos during baking as well as heating up process so taking 1.2 as factory of safety Cengel,et al,. (2003)

Total amount of energy=17,417.16kJ

Design of temporary oil storage tank

Temporary oil storage tank is used to control the fluctuation of temperature on the surface baking pan at the time of pouring batter on the pan and to provide uniform temperature distribution to the pan. So, nanofliud with 4% volume concentration of copper nanoparticle is used to store energy and theoretically temperature of this fluid is maintained at 250^0C.To calculate the volume of storage, thermo physical property of nanofliud is needed. The shape of storage is cylindrical to take the advantage of the shape of pan

Thermo physical properties of the fluid is calculated as follows;

Density of nanofliud is expressed as; -

$\varrho_{nf}=(1-\emptyset)\varrho_f+\emptyset\varrho_p$ 4

Specific heat capacity of nanofliud as; -

$C_{nf}=(1-\emptyset)\varrho_f\ C_f+\emptyset\varrho_p\ C_p/(\varrho_{nf})$ 5

Energy stored =energy required

Table 1: Thermo physical properties of fluids for oil gallery design

No	Material	Density (kg/m3)	Specific heat (kJ/kg.k)
1	Copper	8875	0.412
2	Thermia oil B	713	2.72
3	Nanofliud	1039.48	2.1

Qt=Mnf*C_nf ΔT 6

Where,Qt = amount of energy required= 17,417.16kJ, Mnf=mass of nanofliud

ΔT=(Toil-Tamb) = (250-19) k=231k

Mnf=32kg

For 4% of concentration amount of nanoparticle required is Mnp=1.3kg

Volume of the storage will be calculated by using mass and density of nanofliud

density=mass/volume

Vnf=Mnf/ϱnf 7

Vnf=$0.0345m^3$

Problem occurs during the heating of the oil on the closed system is change on the volume of the oil in the tank. This will Couse break down of the system due to pressure developed during expansion. To prevent this total volume of the storage will be modified to include volume due to expansion

ΔV=βnfVoΔT 8

Where

ΔV =Change in volume due to temperature,βnf =Thermal expansion of nanofliud, Vo=start volume,βf =thermal expansion of Thermia oil B= 0.00076k^(-1),βp=thermal expansion of copper nanoparticle =0.000051k^(-1) Mohammed (2013)

Thermal expression for nanofliud is calculated as

βnf=(((1-Ø)ϱfβf+Øϱpβp)/ϱnf 9

$=9.6*10^{(-6)}\ k^{(-1)}$

ΔV=βnfVoΔT $=3.83*10^{(-5)}\ m^3$

Total volume of oil gallery

VT=ΔV+Vo=0.03453 m^3 10

VT=π/4*D^2*Hg 11

Where;-D =diameter of the pan=0.58m, H=height of the storage tank, VT=total volume of the storage

Hg=(4*VT)/(D^{2*} π)=13cm

Sizing of parabolic trough collector

Table 2: Dimensions for oil gallery

Parameters	Nano fluid	Thermia oil B
Total volume (m3)	0.03453	0.0412
Diameter (m)	0.58	0.58
Height (m)	0.12	0.165

Dimensional analysis for Thermia oil was done by following the same procedure

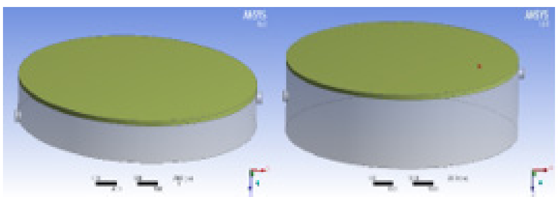

Figure 1: a) Oil gallery with Nano fluid b) Oil gallery with Thermia oil B

Design of collector mainly depends on the amount of power required by a given application. For this system sizing of a collector based on the power required for the baking injera. From the previous calculation energy required per injera is 300.78 kJ. Amount of time required to bake one injera is two minutes up to three minutes Fernández-et al,.(2010). Power required will be calculated as follows.

$\dot{Q}$=Eu/Δt 12

Taking time required =3minutes=180sec

$\dot{Q}$=300.78KJ/180sec=1.671kW

Considering losses through system and taking 1.2 as factor of safety
$\dot{Q}$=2.1kW
The size of collector determined by the amount of power required by the application. Input parameters for collector design are given on the table
Thermo physical properties of the fluid through absorber
T_{flm}=(To+Tin)/2 13
=215^{0}C

Mass flow rate through absorber will be calculated from

Table 3: Input parameters for collector design

Parameters	Value	Source
Inlet temperature	170^{0}C	Assumption made
Outlet temperature	260^{0}C	Fixed
Inner Diameter of the absorber	40mm	From standard of pipe
Diameter of nanoparticle	100nm	High conductivity at smaller size
Receiver temperature	300^{0}C	Assumed value

Table 4: Thermo physical properties of the fluid through absorber

T^0 C	Density (ϱ,kg/m3)	Thermal conductivity (K,w/m.k)	Specific heat (Cp,J/ kg.k)	Thermal expansion 1/k	Dynamic viscosity Kg/m.s 10^{-4}
215	1035	0.2W	2230	0.00066	9.6

Conservation of enrgy equation for steady flow of fluid flowing througn a tube.Power required for baking is 2.1KW this amount of power extracted from the collector
Qu = ṁCp(Tout-Tin) 14
$\dot{m}$=0.0123kg/s
Design of length of the absorber Assumptions
> PTC operates at steady state
> Uniform heat flux over absorber
> Receiver temperature has no great variation along the tube
> There is temperature gradient between receiver and working fluid

Conservation of enrgy equation for steady flow of fluid

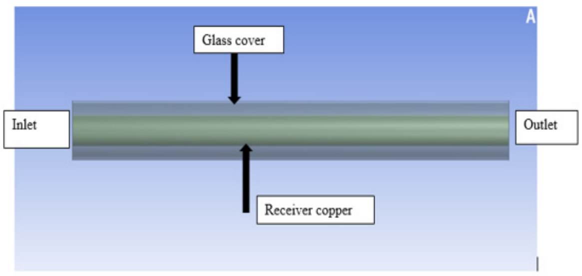

Figure 2: Receiver

flowing througn a tube is given as
The surface temprature of reciever is assumed to be constant along the tube . From Newton's law of cooling, the rate of heat transfer to or from a fluid flowing in a tube can be expressed as Bianco et al.,(2015)
$\dot{Q}$=hAr(ΔTaveg) 15
Where A=heat trasfer area(πDL)
ΔTaveg=averge temprature difference between fluid and the surface
ΔTaveg can be approxmatly expressed as arithematic mean temprature difference
ΔTam=(ΔTi+ΔTe)/2 16
ΔTin=(Tr-Tin) =130^0 C
ΔTe=(Tr-To)= 40^0 C
ΔTam=(140^0 C+10^0 C)/2=85^0 C
Ar=$\dot{Q}$/hΔTam=0.34 m^2
Area of recievr is given as

Ar=πDL 17
L=Ar/πD=2.5m
Area of the parabola
The available solar energy on the collector aperture is the product of the direct beam solar irradiation and of the collector aperture Mohammed,(2013)
Qs=Ib*Aa 18
Thermal efficiency of the system is given as
η_{th}=Qu/Qs 19
The efficiency range of most solar concentrators is 40%-60% Kumar et al,.(2018). The concentration ratio for this kind of application is around 20 Korres et al,. (2019). Concentration ratio is given as aperture area divided by the area of the receiver. The area of receiver was calculated above so he only unknown parameter was area of the parabola.
CR=A_a/A_r 20
Aa=6.8m^2
Length of the parabolic trough is equal to the length of the absorber
Aa=L*W 21
W= 2.53m
Thus, the thermal efficiency of the collector becomes 49.02%.

RESULT AND DISCUSSION

The average family size of five, the amount of injera required per day is 15. The total amount of energy required for the baking is17412.16 kJ. Temporary oil storage is design for both nanofliud and conventional fluid. The table below shows their results
From the above result it was observed that the use of nanofluid as heat transfer fluid reduce the size of equipment.
Due to enhanced thermo physical property of nanofliud

Table 5: Comparison of the results for both fluids

Parameters	Nano fluid	Thermia oil B
Total volume (m3)	0.03453	0.0412
Diameter (m)	0.58	0.58
Height (m)	0.12	0.165

heat transfer rate is high compared with conventional fluid. This reduces the baking time of injera and saves energy as well.

Parabolic trough collector was designed based on the energy consumption analysis of baking process. Area of parabola is $6.8m^2$ and its width is 2.53m with the length of 2.5m.Thermal efficiency is 49.02%.

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. Parabolic trough collector is used as a heat collecting element and heat is transported from PTC to the kitchen by using heat transfer fluid. From the design process it was observed that the use of nanofluid reduce the size of commoponanats when we compare with other types of conventional fluids such as water and shell Thermia oil. The design result shows that the use of nanofluid as heat transfer media is more advantageous than the use of conventional fluids but, for the future development of the system and comparing the result by using both types of the fluid is required.

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