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COMPARATIVE STUDY OF NANOFLUID AND CONVENTIONAL FLUID HEAT TRANSFER CHARACTERISTICS USING CFD SIMULATION FOR SOLAR THERMAL INJERA BAKING

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Abstract — *In this paper, CFD analysis for solar thermal injera baking method is carried out by using ANSYS fluent package. Two types of fluids are used nanofluid (cu/shellthermia oil B) and shell Thermia oil Heat transfer fluid is heated by using a solar parabolic trough collector and circulate through space below the baking pan in the kitchen. Part of the fluid was stored below the pan to control temperature fluctuation on the surface of the pan and keep the system at steady condition during baking. The main parameter used for comparison of the performances of the fluid used is heat up time. Heat up time is the time required to raise the temperature of the surface of the pan from the room (19^0C) to the optimum baking temperature ($180^0C - 220^0C$).The main objective of this paper is to reduce heat- up time and attain maximum temperature on the surface of the pan. Nanofluid used was Cu/shell Thermia oil B with a volume concentration of 4% of the nanoparticle. Thermo-physical property for the nanofluid was calculated using theoretical models obtained from the literature. Simulations show that heat up time for the baking pan was enhanced by 43.6% using nanofluid and maximum temperature on the surface of the pan was registered* 195^0

Keywords CFD simulation, heat up time, injera baking pan, nanofluid**,** PCM

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I. 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 [1].

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 [2]. 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 [3]

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 address 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. Nanofluid 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 transfer.

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. Another alternative source for injera baking is electricity but it has high fluctuation and not available in rural area. Solar energy is used as energy sources for injera baking process. The use of solar energy reduces the problem mentioned above but, it requires efficient collection and transferring. Cu/shell Thermia oil B nanofluid is used to enhance the efficiency of the system. Injera baking process requires large amount of temperature 180^0C $-$ 220^0C [1]. 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 400^0C could be obtained with parabolic through collectors (PTCs). PTCs can effectively produce heat at temperatures between 50^0C and 400^0C [4]. Open fire injera baking method is the most common baking method in Ethiopia. This traditional method of baking causes high amount of energy loss and also is unhealthy because of carbon inhalation to the lungs and irritation of eyes. [5, 6].

Figure. 1 a) Open fire injera baking method b) Electricity powered injera baking pan

Electricity powered injera baking method is also familiarized in Ethiopia but it consumes high amount of energy and also available only on the urban area of the country [6] In solar thermal injera baking method the radiant energy from the sun is converted to the heat energy by using solar collector and this heat energy is circulated through the system by heat transfer fluid. Abdulkadir et al. [7], studied the performance of injera baking pan for indoor cooking. From their experimental result, they were observed that it took approximately 1hour for heating oil to 300^0C and 40 minutes to reach the optimum baking surface temperature. Injera is removed from the baking pan every two minutes and it takes an idle time of three minutes between each injera to recover to optimum baking temperature. Based on average family size, 20 injera can be baked per day in approximately three hours and 28 minutes. Abdulkadir A. Sisay B. et al. [8], investigated the probability of baking injera by glass pan. Solar thermal energy transferred to the kitchen by means of a circulating heat transfer fluid heated by solar energy concentrated by a parabolic trough. They used an electric heater for simulation purposes and obtained 191^0 C temperature on the surface of the pan. Hassen and Amibe [3], developed a finite element model for solar-powered injera baking oven for indoor cooking. They used 8mm thickness ceramic pan for their investigation and study the heat-up time and temperature distributions during initial heat-up and cyclic baking of the new model. Finally, they concluded from their simulation result that the heat up time can be reduced by reducing the thickness of the baking pan for a given supply oil temperature. This baking system gives reasonable heat up and baking time for 8mm thick ceramic pan with a heated oil temperature of275^0 C. Asfafaw et al. [1], introduced a new injera baking solar thermal method which use the direct steam to heat the surface of the baking pan. Their experimental result shows that the quality of Injera in the range of 135^0 C -220^0 C remains the same, however, a slightly baking time difference was observed. *Arul et al.* [9] estimated thermophysical properties of nanofliud by using theoretical models. They improved thermophysical properties of conventional fluids by suspending nanoparticles.

Table 1.Theorotical models to calculate thermophysical properties of the nanofluid [9, 10]

No	Property of nanofliud	Model
1	Specific heat (KJ/kg.k))	$C_{nf} = \frac{(1-\emptyset)\rho_f C_f + \emptyset \rho_p C_p}{\rho_{nf}}$
2	Density (kg/m3)	$\rho_{nf} = (1-\emptyset)\rho_f + \emptyset\rho_p$
3	Prandtl number	$Pr = \frac{v_{nf}}{\alpha_{nf}}$
4	Dynamic viscosity	$\mu nf = \frac{\mu_{bf}}{(1-\emptyset)^{2.5}}$
5	Thermal diffusivity	$\alpha nf = \frac{k_{nf}}{(\rho cp)_{bf}}$
6	Volumetric thermal expansion	$\beta nf = \frac{((1-\emptyset)\rho f\beta f + \emptyset\rho p\beta p}{\rho nf}$

Where ρ_{nf} =density of nanofliud, $\emptyset$=Nanoparticle percent concentration, ρ_f=density of base fluid, ρ_p=density of nanoparticle, C_{nf}=heat capacity of nanofliud C_f heat capacity of base fluid C_p heat capacity of nanoparticle. Previously shell Thermia 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 pan is low. This increases heat up time for injera baking pan. 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 cupper) 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.

II. II. DESCRIPTION OF SOLAR THERMAL INJERA BAKING SYSTEM

The proposed system uses solar parabolic trough collector to convert radiation in to heat energy. The block diagram of the whole system is shown in the figure below. The system contains parabolic trough, pump, injera baking pan, temporary oil storage, oil storage and pipes. Heat transfer fluid coming from the trough gives up heat to the pan and part of the fluid is stored on the oil gallery below the injera baking pan in order to overcome sudden drop of baking pan top surface temperature below optimum range ($180^0C - 220^0C$).Pump is used to drive fluid through the system.

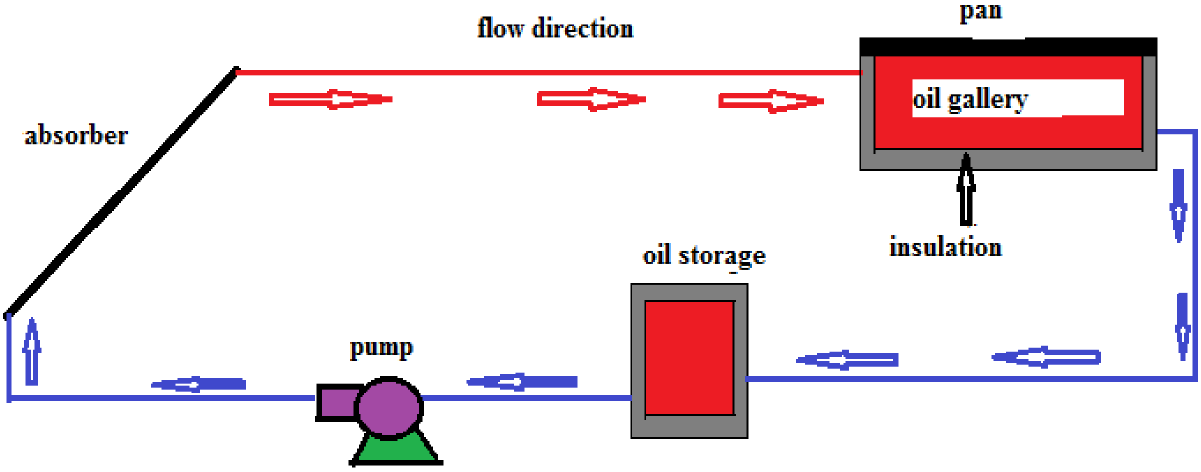

Figure 2.Schematic diagram of solar thermal injera baking method

III. HEAT TRANSFER ANALYSIS FOR INJERA BAKING PAN (MITAD)

The top surface of baking pan is exposed to convective and radiation heat transfer with the ambient. Convective heat transfer coefficient is given as;

$$hc = \frac{NuK}{L} \tag{1}$$

Where: hc =convection heat transfer coefficient,
Nu =Nusselt number, K =Thermal conductivity
L_c= characteristic length
Some dimensionless parameters are used on the calculation of convective heat transfer coefficient.
Reynolds number (Re)

$$Re = \frac{\rho Vl}{\mu} \tag{2}$$

Prandtl number (Pr)

$$Pr = \frac{v}{\alpha} \tag{3}$$

Grashof number (Gr);

$$Gr = \frac{g\beta\Delta TL^3}{v^2} = \frac{\rho^2 g\beta\Delta TL^3}{\mu^2} \tag{4}$$

Rayleigh number (Ra);

$$Ra = Gr * Pr \tag{5}$$

Nusselt number for heat transfer to and from horizontal plat at constant heat flux is experimentally produced as;

$$Nu = 0.13(Gr * Pr)^{1/3}) \qquad GrPr<2*10^8 \tag{6}$$

$$Nu = 0.16(Gr * Pr)^{1/3}) \qquad 2*10^8<GrPr<10^11 \tag{7}$$

In these equation all properties except volumetric expansion are evaluated at Te [11].

$$Te = Tpan - 0.25(Tp - Tamb) \tag{8}$$

$$\beta \text{ will be evaluated at } Tamb + 0.25(Tp - Tamb)$$
$$\beta = 1/T \tag{9}$$

Characteristic length for circular disk taken as 0.9D where D is the diameter of the pan [30].
Radiation heat transfer coefficient is given as;

$$hr = \varepsilon\sigma(Tp + Tamb)(Tp^2 + Tamb^2) \tag{10}$$

Where; hr =Radiation coefficient ε =Emissivity of the surface =0.95 [31] σ =Stefan Boltzmann coefficient (5.67x10^-8 W/m2K4).
To compare the performance of the system two types of the fluid was used (shell Thermia oil B and nanofluid).Their thermal properties were calculated based on the inlet temperature.

Table 3.Thermophysical properties of the fluids

Property	Nanofliud	Thermia oil
Thermal conductivity W/m.K	0.14	0.126
Convective heat transfer coefficient W/m^2.K	437	359.75

IV. COMPUTATIONAL FLUID DYNAMIC ANALYSIS OF THE SYSTEM

ANSYS (fluent) is used to solve physical problems by using a finite volume method that discretizes a given demine into smaller control volumes to apply conservation equations. The simulation for Injera baking pan with temporary oil storage tank is performed on ANSYS (fluent) 16.0 software. The governing equations used for this analysis were energy equations, Continuity equations and momentum equations.

A. Geometry The geometry of the system modeled by ANSYS design modeler. The system contains baking pan on the upper part, temporary oil gallery with inlet from collector and outlet to the oil storage, and part of fluid stored below the pan was also modeled. The numerical simulation are carried out on CFD software package ANSYS fluent (v16.0).For comparison purpose nanofluid and shell Thermia oil B were used as heat transfer fluid. Comparison based on heat up time, surface temperature of the pan and temperature of the fluid on the oil gallery.

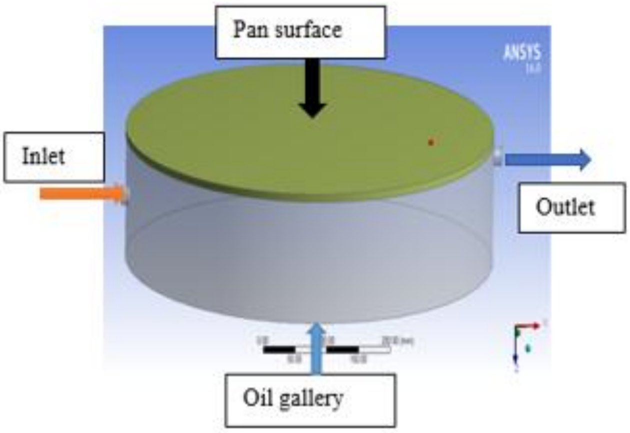

Figure 3.Model

Table 3. Input parameters for CFD analysis

Parameters	Values
Baking pan material	Clay
Baking pan diameter	60cm
Baking pan thickness	8mm
Heat capacity of the pan	$880J/k.kg$
Conductivity of pan	$0.45W/m.k$

Heat is transferred from oil to the bottom surface of the pan by convection then through pan by conduction to the injera, the upper surface of the pan is exposed to the environment and heat lost to the environment by convection and radiation.

B. Mesh generation

Meshing is a method of dividing the flow domain into many elements or subdomains. Equations are solved in those domains. 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 cheeked by performing mesh sensitivity analysis. Steady state analysis was used to check mesh sensitivity for oil gallery and pan assembly using two parameters temperature of the pan and storage.

Table 4. Mesh sensitivity analysis

Mesh size(mm)	Pan Temperature (k)	Storage temperature (k)
15	483.67	569.8
10	494.96	569.63
5	506.68	569
3	506.7	568.69
1	506.92	568.92

For different element size mesh sensitivity analysis was done to identify best element size. From the above table it was obtained that the temperature was almost constant for mesh size 5mm.Graphicaly mesh sensitivity analysis was represented below

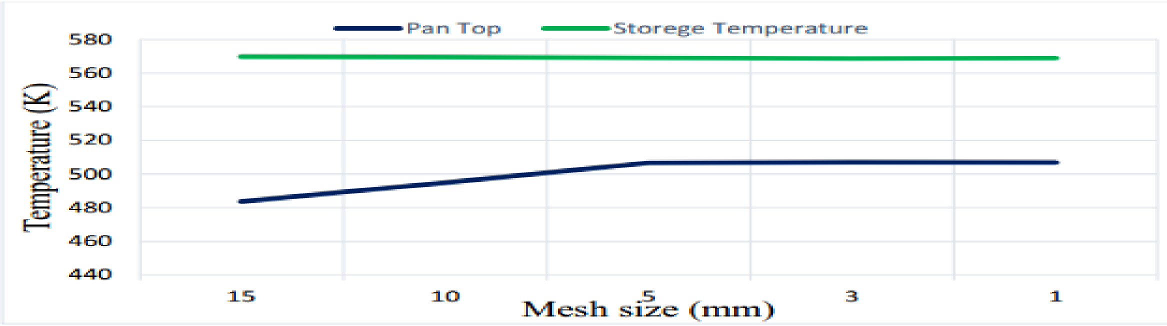

Figure 4.Mesh sensitivity

From Fig. 5, it was observed that there was no effect of mesh size on the study parameter after 5mm and the selected mesh size for this analysis was 3mm.

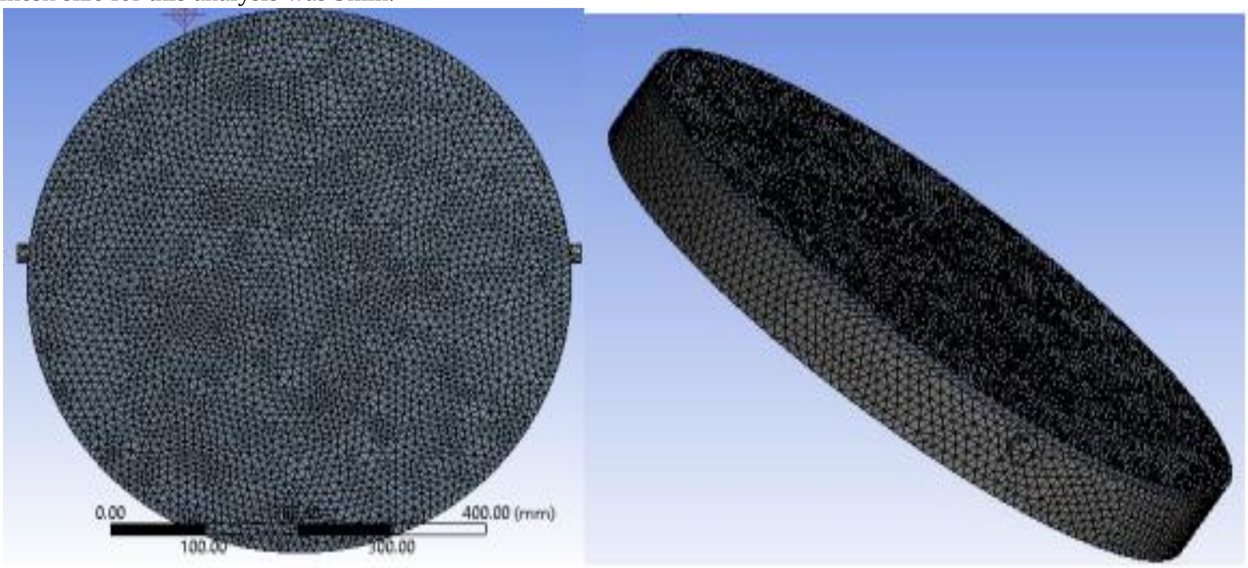

Figure 5 Meshing of pan

B. Boundary condition

Boundary conditions were required for simulation of the system.

Table 5.Boundary conditions

Boundary	Conditions
Inlet	Mass flow of (0.0123kg/s) and temperature of (250^0C)
Outlet	Outflow
Oil gallery walls	Adiabatic
Pan body	Conduction
Top pan surface	Convection and radiation to the ambient
Interface (pan and fluid)	Convection

Based on the above input data heat up time (the time required to rise the temperature of the surface of pan from ambient condition to the baking temperature (180^0C)) and temperature distribution on the surface of pan analyzed.

V.RESULTS

The baking pan transient temperature profile and temperature distribution on the surface of pan was discussed on the following section. Simulation was conducted for two types of fluid (for nanofluid and shell Thermia oil B).

A.Heat up time of the pan using nanofliud as HTF

From the simulation results, heat up time for the pan and oil on the gallery was obtained. First part of simulation result was using nanofluid as heat transfer media and the time required to reach the baking temperature was obtained from the simulation second part of simulation results were for conventional fluid. Finally the results were compared in order to get efficient working fluid.

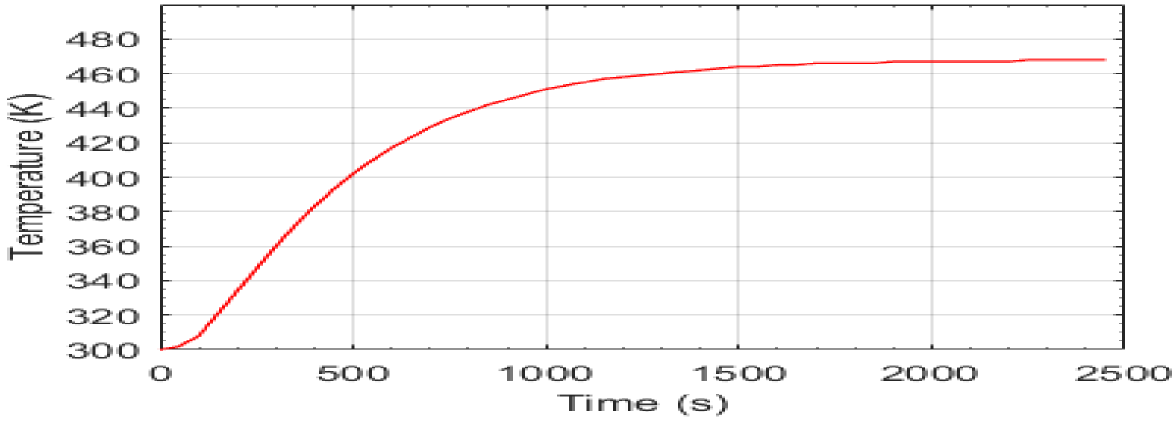

Figure 6 Heat up time for pan using nanofluid

Figure 6 Shown above is the temperature in K versus time in second which shows the time required to reach maximum temperature on the surface of the injera baking pan when the surface of pan exposed to convection and radiation losses from the top and for the given boundary condition. The maximum temperature obtained at the surface of the pan is 468K ($195^0 C$) and the time required to reach this temperature is 1900sec (31minutes).The pan surface was at the steady condition for this temperature and there is no change for temperature on the surface of the pan as time increase further.

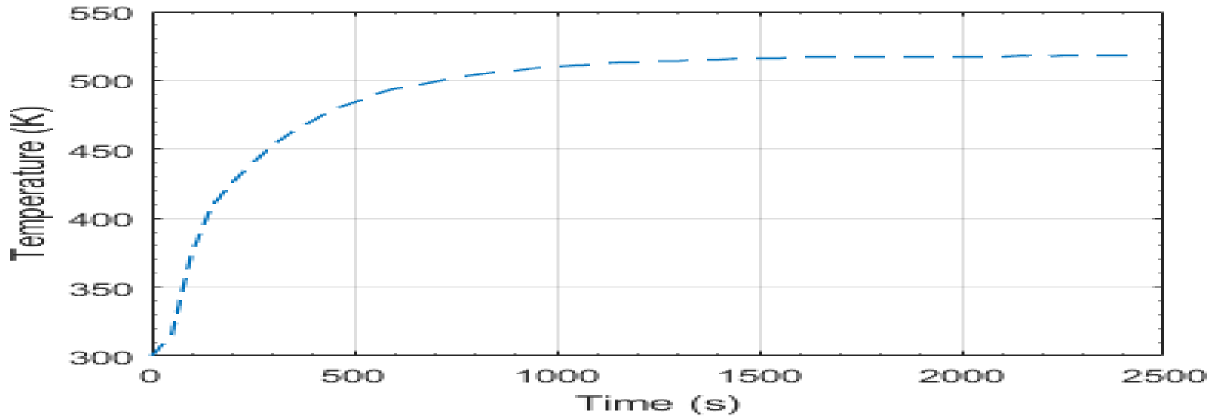

Figure 7.Heat up time for oil on the oil gallery using nanofluid

Figure 7 Shown above also temperature versus time graph for the nanofluid on the oil gallery (temporary oil storage) it shows the maximum temperature of the oil on the gallery with respect to the time required to reach that temperature. The Maximum temperature obtained on the oil gallery was 518K ($245^0 C$) at a time of 1600sec (27minutes).The system was steady beyond this time.

B.Heat up time using shell Thermia oil B as HTF

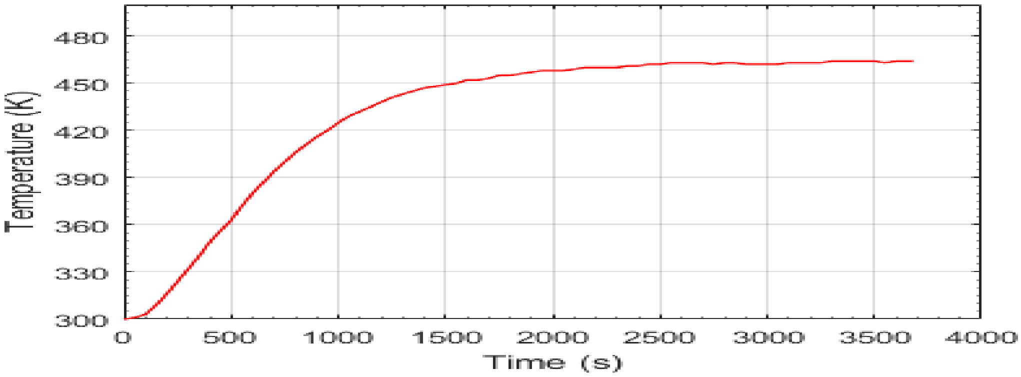

Figure 8.Heat up time for pan using shellthermia oil B

Figure 8 Shown above is temperature in K versus time in second which shows the time required to reach maximum temperature on the surface of the injera baking pan when the surface of pan exposed to convection and radiation losses from the top and given boundary condition. The maximum temperature obtained at the surface of the pan is 464K ($191^{0}C$) and the time required to reach this temperature is 3300sec (55minutes).The pan surface was at steady condition for this temperature and there is no change for temperature on the surface of pan as time increase further

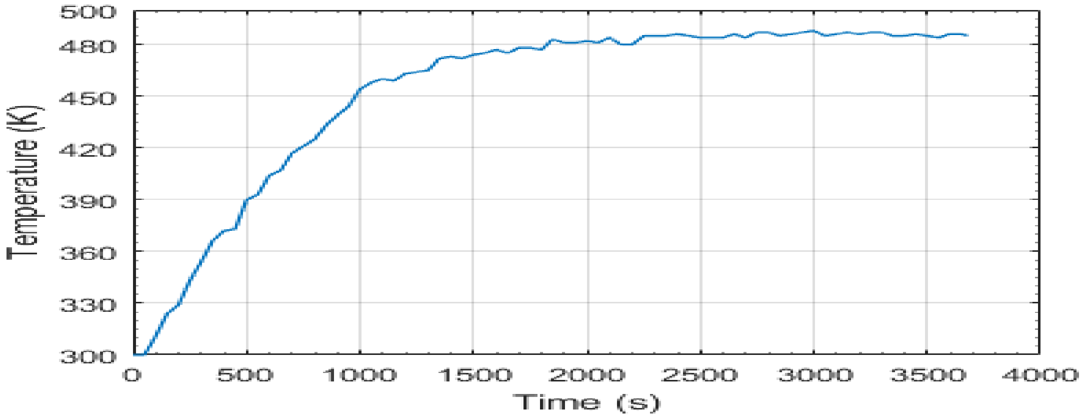

Figure 9 Heat up time for oil on the oil gallery using shellthermia oil B

Figure 9 Shown above also temperature versus time graph for the nanofliud on the oil gallery (temporary oil storage) it shows maximum temperature of the oil on the gallery with respect to the time required to reach that temperature. Maximum temperature obtained on the oil gallery was 487K ($214^{0}C$) at time of 2750sec (46minutes).The system was steady beyond this time.

C.Heat up time comparisons for nanofluid and shell Thermia oil B

Comparisons of the performances of the two working fluids were based on the heat up time and maximum temperature obtained on the surface of the baking pan. Fluid that take short period of time to maintain optimum baking temperature on the surface of the pan is recommended for this system. Because of solar energy is time dependent type of energy which means it is applicable only day time so, efficient use of this energy is required.

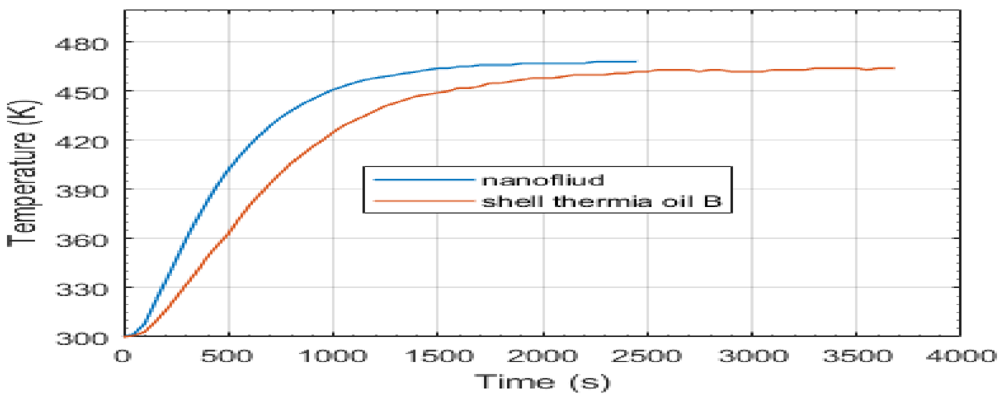

Figure 10. Heat up time for pan

Figure 10 Shows heat up time for Injera baking pan for nanofliud and conventional fluid (shell Thermia oil B) as heat transfer media. From the figure it was observed that time required to heat the surface of the pan is smaller for nanofliud than that of conventional fluid due to its high thermo physical properties. The pan surface have maximum temperature of $195^0\,C$ at time of 31 minutes for nanofliud. For shell Thermia oil B the maximum temperature on the surface of pan was $191^0\,C$ at time of 55 minutes.

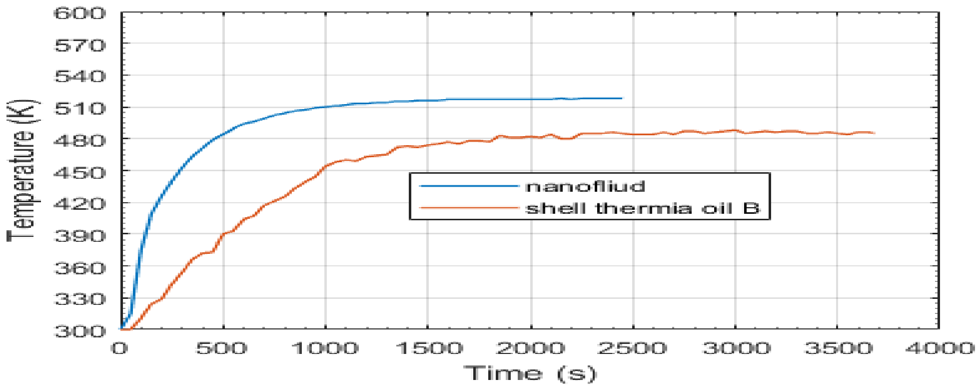

Figure11. Heat up time for oil on the oil gallery

Figure 11Shows temperature versus time graph for nanofliud and shell Thermia oil on oil gallery. From the result it was observed that the time required to reach steady state for nanofliud is smaller than that of shell Thermia oil B.

VI.CONCLUSION

From the CFD modelling and simulation, the heat up time for the pan and fluid on the oil gallery was obtained. From simulation it was seen that it took 31 minutes to reach a maximum temperature of $195^0\,C$ on the surface of the pan using nanofliud and, it took 55 minutes to reach a maximum temperature of $191^0\,C$ on the surface of the pan using shellthermia oil. The result of this simulation showed that the use of nanofluid reduce heat up time (43.6%) for the baking pan and maximum temperature on the surface of the pan was obtained.

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