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Research Article

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Posted Date: April 26th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-342471/v1>

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Performance Analysis of Solar Chimney Power Plant from Geothermal Waste Heat Source a Case of Aluto-Langano, Ethiopia.

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Abstract

In this paper, the transient thermal simulation on working fluid of solar updraft power plant using waste water was investigated to characterize the enhancement by numerical and theoretical method. Numerical solution technique used to solve a differential equation form of governing equations using finite difference discretization scheme. Most of the researches done on geometrical parameters to perform the mathematical modeling. This paper combines some of the above improvements on the performance of plant and combines them with new idea of heat source as waste heat in Aluto Langano geothermal power plant. Moreover, this study using dimensions of plant constructed in Manzanares, Spain height of chimney =194.6 m, diameter of collector=244 m, diameter of chimney=10.16 m.

The obtained result, the collector temperature increases by 7 °C, the pressure potential is found 182.82 Pa, the pressure drop on the turbine was 121.88 Pa, the pressure loss was 60.94 Pa and the power output 123.59 kW. As a result, the collector efficiency increases to 43.58% and the overall efficiency of plant to 0.242%.

Key: solar chimney, collector efficiency, thermal simulation

Modeling of the Collector Roof, chimney and turbine

Correspondingly, the following assumptions are taken to avoid complexity of mathematical model:

- Temperature rises in the solar collector is along radial direction [1]
- The collector roof and ground temperature has no variation along collector radius and thickness [2]
- Insignificant variation of velocity and temperature along chimney cross-section.
- The flow is one-dimensional, unsteady and inside parallel plate flow.
- Boussinesq assumption is valid for the airflow inside the tower [3]
- No heat loss throughout the chimney.
- The temperature at some depth below the ground surface is constant.
- There is no radial conduction in the ground surface

1.1. Mathematical model for collector

The mathematical model of the collector is done based on the figure 1.1 and figure 1.2. The energy balance equations are;

The continuity equation

$$\frac{d}{dr}(\rho u A) = 0 \dots\dots\dots (1.1)$$

Momentum equation

$$-\rho u \frac{du}{dr} = \frac{dp}{dr} + \rho g \frac{dh}{dr} \dots\dots\dots (1.2)$$

Energy equation

$$\frac{dq}{dr} = -\frac{q''}{m} \frac{dA}{dr} = c_p \frac{dT}{dr} + u \frac{du}{dr} + g \frac{dh}{dr} \dots\dots\dots (1.3)$$

State equations

$$\frac{dp}{p} - \frac{d\rho}{\rho} - \frac{dT}{T} = 0 \dots\dots\dots (1.4)$$

Figure 1. 1 Energy of collector roof

Figure 1. 2 Geometry of plant with heat source

1.2. Energy Balance and Discretization of Collector Roof

For roof:

$$A_{roof}I_{roof} + q_{r,pr} + q_{r,gr} = q_{con,rf} + q_{con,ra} + q_{r,rsky} + c_{pr}\rho_r \frac{dT_r}{dt} 2\pi r_r dr_r dz_r \dots \dots \dots (1.5)$$

For air

$$\dot{m}c_p \frac{dT_f}{dt} = q_{con,rf} + q_{con,pf} + q_{con,gf} - \dot{m}c_p \partial \frac{T_f}{\partial r} dr \dots \dots \dots (1.6)$$

For geothermal pipe

$$A_{pipe}I_p + q_{r,rp} + q_{r,gp} + \frac{2\pi l_p k_p}{\ln\left(\frac{r_2}{r_1}\right)} (T_w - T_p) = q_{con,pf} + c_{pp}\rho_p 2\pi r_p \frac{dT_p}{dt} dr dz_p \dots \dots \dots (1.7)$$

For the ground storage

$$A_{ground}I_g + q_{r,rg} + q_{r,pg} - A_{ground}h_{con,gf}(T_g - T_{fm}) = c_{pg}\rho_g 2\pi r \frac{dT_g}{dt} dr dz \dots \dots \dots (1.8)$$

1.3. Available Pressure Capacity due to Slanted Roof and Tower

The tower converts the temperature difference to the velocity of air. The rising of temperature creates the density difference in the collector that works as the driving force for fluid air. By taking the air as a working fluid, the whole pressure capacity converts to the moving pressure of airflow. In variable density assumptions, air is an ideal gas, and insignificant loss throughout the chimney wall. A mathematical equation developed to investigate the efficiency of the plant under conservation of energy and momentum principle.

The frictionless momentum equation express as;

$$-\rho u \frac{du}{dr} = \frac{dp}{dr} + \rho g \frac{dh}{dr} \dots \dots \dots (1.9)$$

The increased pressure capacity to drive flow of air from the roof inlet to chimney outlet written as:

$$\Delta P_{poten} = \frac{1}{2} \rho_3 u_3^2 \dots \dots \dots (1.10)$$

After integration of Eq. (1.9) can written as;

$$\int_1^3 \rho u du = \frac{1}{2} \int_1^3 \rho du^2 = p_1 - p_3 - g \int_1^3 \rho dh \dots \dots \dots (1.11)$$

The integral part of the Eq. (1.11) eliminated by inserting the average density of working fluid inside the roof into Eq. (1.10) can be rewritten as:

$$\frac{1}{2}\bar{\rho}(u_3^3 - u_1^3) = p_1 - p_3 - g\bar{\rho}H_{coll} \dots \dots \dots (1.12)$$

In addition, the expression Eq. (1.12) of the slanted collector pressure capacity Δp_{poten} can be written as;

$$\Delta p_{poten} = p_{\infty 1} - p_3 - \frac{\rho_{\infty 1} + \rho_3}{2} g H_{coll} \dots \dots \dots (1.13)$$

At an arbitrary position, the height of collector described by radius and the inclination angle β :

$$h = H_{coll} - r \sin \beta \dots \dots \dots (1.14)$$

The effective tower height H_{eff} for the Plant defined as the sum height of collector, H_{coll} , and the chimney height, $H_{chimney}$.

$$H_{eff} = H_{coll} + H_{chimney} \dots \dots \dots (1.15)$$

The frictionless adiabatic flow of the dry air experiences no entropy changes in the process and is defined as:

$$\frac{P}{\rho^\gamma} = \text{constant} \dots \dots \dots (1.16)$$

$$\rho = \frac{P}{RT} \dots \dots \dots (1.17)$$

$$\frac{p_1}{p_2} = \left(\frac{T_1}{T_2} \right)^{\frac{\gamma}{\gamma-1}} \dots \dots \dots (1.18)$$

$$\frac{\rho_1}{\rho_2} = \left(\frac{T_1}{T_2} \right)^{\frac{1}{\gamma-1}} \dots \dots \dots (1.19)$$

The gas constant of dry air is $R = 287 \text{ J/kg.K}$. Temperature varies with altitude equal to 0.00975 K/m .

$$T = T_o + \frac{g}{R} \frac{1-\gamma}{\gamma} h \dots \dots \dots (1.20)$$

The relation between ambient air static temperature and height is described as:

$$\frac{T_{\infty}}{T_{\infty 0}} = 1 - \frac{gh}{c_p T_{\infty 0}} \dots \dots \dots (1.21)$$

Where, $T_{\infty 0}$ is the atmospheric air temperature at sea level .

The variation of pressure due to gravity is given by:

$$\frac{dp}{dz} = -\rho g \dots \dots \dots (1.22)$$

After substitution of Eq. (1.18) into Eq. (1.21) we get

$$p_3 = p_4 \left(1 - \frac{gH_{sut}}{c_p T_3} \right)^{\frac{-\gamma}{\gamma-1}} \dots \dots \dots (1.23)$$

$$p_3 = p_{\infty 1} \left(\frac{1 - \frac{gH_{eff}}{c_p T_{\infty 1}}}{1 - \frac{gH_{sut}}{c_p T_3}} \right)^{\frac{\gamma}{\gamma-1}} \dots \dots \dots (1.24)$$

$$\frac{T_4}{T_3} = 1 - \frac{gH_{sut}}{c_p T_3} \dots \dots \dots (2.25)$$

$$\frac{T_{\infty}}{T_{\infty 1}} = 1 - \frac{gh}{c_p T_{\infty 1}} \dots \dots \dots (1.26)$$

$$\frac{p_{\infty}}{p_{\infty 1}} = \left(1 - \frac{gh}{c_p T_{\infty 1}} \right)^{\frac{\gamma}{\gamma-1}} \dots \dots \dots (1.27)$$

And the static pressure $p_{\infty 4}$ of dry atmosphere given by:

$$p_{static, \infty 4} = p_{static, \infty 3} \left(1 - \frac{gH}{c_p T_{\infty 3}} \right)^{\frac{\gamma}{\gamma-1}} \dots \dots \dots (1.28)$$

$$\Delta p_{poten} = p_{\infty 1} \left(1 - \left(\frac{1 - \frac{gH_{eff}}{c_p T_{\infty 3}}}{1 - \frac{gH_{sut}}{c_p T_3}} \right)^{\frac{-\gamma}{\gamma-1}} \right) - \frac{gH_{coll} p_{\infty 1}}{2RT_{\infty 1}} \left(1 + \frac{T_{\infty 1}}{T_3} \left(\frac{1 - \frac{gH_{eff}}{c_p T_{\infty 3}}}{1 - \frac{gH_{sut}}{c_p T_3}} \right)^{\frac{-\gamma}{\gamma-1}} \right). (1.29)$$

The pressure potential converted to dynamic pressure calculated as:

$$\Delta p_{total} = \Delta p_{poten} - \Delta p_{loss} \dots \dots \dots (1.30)$$

The thermal efficiency of the plant defined as the ratio of the fluid power of the air flow at the tower inlet to incoming solar radiation to air flow obtained from the slanted collector. It can also define as thermal energy to kinetic energy, which mainly determined by atmospheric temperature T_0 at sea level and chimney high H_{ch} [3, 4].

$$\eta_{ch} = \frac{\frac{1}{2} \dot{m}_f u_f^2}{\dot{m}_f C_p (T_{f2} - T_{f1})} = \frac{g H_{ch}}{c_p T_0} \dots \dots \dots (1.31)$$

The efficiency of collector roof is the ratio of useful energy transferred to the fluid air to the incoming solar radiation intercepted by the roof and the heat generation from the geothermal power plant waste heat.

$$\eta_{coll} = \frac{Q_{usefull}}{I_T A_{coll} + Q_{geo}} = \frac{\dot{m}_f c_{pf} (T_{f2} - T_{f1}) + 0.5 * \dot{m}_f (u_2^2 - u_1^2)}{I_T A_{coll} + \dot{m}_w c_{pw} (T_{w2} - T_{w1})} \dots \dots \dots (1.32)$$

Result and Discussion

The initial condition of the plant on Aluto Langano weather condition are tabulated in Table 3.1 by using this initial conditions numerical solutions are solved. The simulation result of the Figure 3.7 is tabulated in Table 3.2.

Table 3. 1 Assumed and Initial Condition

Initial condition		Assumed condition	
Parameter	Value	Parameter	Assumed value
Ambient temperature, T_a	18 °C	Roof temperature, T_r	50 °C
Inlet air temperature, T_{f1}	18 °C	Outlet airtemperature, T_{f2}	45 °C
Inlet geothermal water temperature, T_{w1}	90 °C	Ground temperature, T_g	60 °C
Outlet geothermal water temperature, T_{w2}	$T_a + 20$ °C	Geothermal water pipe temperature, T_p	55 °C
Mass flow rate of geothermal water, $\dot{m}_w$	62.5 kg/s	Mass flow rate of fluid air, $\dot{m}_f$	1525 kg/s
Specific heat capacity of water	4190 J/kg.K		

Table 3. 2 The Output Parameter at Each Section of Plant

State	Pressure (Pa)	Temperature (°K)	Density (kg/m ³)	Velocity (m/s)
state1	90000	293	1.0703	3
state2	89901	318	0.98505	15.801
state3	89783	319	0.98067	7.909
state4	99044	317.1	1.0883	14.936
	$\Delta p_{\text{poten}}=182.82 \text{ Pa}$	$\Delta p_{\text{turb}}=121.88 \text{ Pa}$	$\Delta p_{\text{loss}}= 60.94 \text{ Pa}$	$\Delta P_{\text{load}}=123.59 \text{ kW}$

In Figure 3.1, four Figures plotted together which shows annual temperature variation of roof, ground, fluid airflow and pipe. The highest fluid air temperature observed in the month of November, December and January; which is approximately 323.3°K. The minimum temperature observed in august. The temperature profile of all figures is similar in shape as shown, which shows the ground temperature is the maximum observed temperature because of the ground is acts as absorber in the system. It absorbs the incoming solar radiation and emits back to the collector roof and fluid air in the collector.

Figure 3. 1 Annually Temperature Variation of Roof, Ground, Fluid Air and Pipe

In Figure 3.3, the daily variations of the representative day of January are plotted. The maximum temperature observed in the time between 10 A.M and 13 P.M for all graphs as shown, which is the maximum solar radiation, occurred. The temperature range of the fluid air is smaller than that of others; this indicates the power output of the plant is nearly constant throughout the day. To show the effect of geothermal water waste heat on the fluid air, Figure 3.2 and Figure 3.3 compared. The increasing recorded temperature is the combined effect of solar radiation and geothermal water waste heat from geothermal power plant.

Figure 3. 2 Daily Temperature Variation of Roof, Ground, Fluid Air and Pipe

Figure 3. 3 The Output Temperature of Fluid Air without Geothermal Water

Figure 3.4 indicates effect of solar insolation and roof radius on temperature graph air inside collector. keeping incoming radiation constant, the temperature of working fluid increases towards the collector outlet and reach maximum at collector outlet. Figure 3.4 also imply that, for the same collector radius increasing the incoming insolation increases air temperature. When solar radiation increases the collector surface temperature increases and hence the fluid air temperature. But as the incoming insolation above some level, the collector surface temperature increases more and then high convection occurs which results in decrease the mass flow rate of fluid air in the roof.

Figure 3. 4 Temperature of Fluid Air at any Radius of Collector

Figure 3.5 shows the static pressure profile, which decreases towards the collector out let and the minimum value observed at the chimney base. It also demonstrates that keeping collector radius is constant and incoming radiation results in a decrease in the static pressure. Figure 3.7 shows the air velocity profile through the collector. The velocity increases through the collector towards the collector outlet radius, but it increases rapidly at chimney base. When the collector radius is constant, an increase of solar radiation causes an increase of the air velocity. Examining the effect of collector radius on static temperature and velocity, the trend developing in Figure 3.5 and 3. 7 respectively, have the same effect with the pressure and velocity graphs [5].

Figure 3. 5 Static Pressure versus Radius of Collector

The effect of changing dimensions of the solar chimney power plant on the power generation ranging from 60 to 120 m and chimney height from 50 to 450 m is shown in Figure 3.6 below. These results demonstrate that the larger the collector size and the higher the chimney height is, the greater the power generation will be. It is also evident that the power generation of solar chimney increases nonlinearly with the increase of collector diameter and chimney height. It increases sharply when the sizes of collector and the chimney are small, but slowly with an increase in size. In this study about 123 kW electric power can be produced in the solar chimney when the diameter of the collector is 244 m, and the chimney height is 194 m.

Figure 3. 6 Power Output versus Chimney Height and Collector Radius

Figure 3. 7 Velocity of Fluid Air versus Radius

Figure 3.8 presents the efficiency is improved due the use of hybrid solar-geothermal energy from 32 % to 43.58 %.

Figure 3. 8 Efficiency of Plant with and Without Geothermal Power Plant

Conclusion

In this work, the performance investigation of a solar chimney power plant using a heat source from geothermal power plant is done. The obtained results shows with waste heat of geothermal power plant with mass flow rate 62 kg/s and 90 °C, the collector temperature increases from 316 to 323 K with combined effect of geothermal water and solar radiation as shown in Figure 3.2 and Figure 3.3.

The change in temperature is 27 °C, which is 7 °C increment with Manzanares proto type as shown in Table 3.3. The maximum velocity achieved at the outlet of collector is 15.8 m/s and 182.8 Pa

potential pressures observed at the chimney inlet. The total pressure drop at the turbine is 120.4 Pa and 62.3 Pa pressure loss occurred due to inlet pressure loss to collector and turbine. The amount of power output increases from 50 kW to 123 kW and efficiency of the collector increases from 32% to 43.58%. Hence, the total efficiency of the plant increased from 0.176% to 0.242%.

Table 3. 3 Comparisons of this Work and Previous Works on Reference Plant

Parameter	Schalachi, (2005)	Asnaghi et al., (2011)	Koonsrisuk and Chitsomboon ,(2003)	In this work	FLUENT
V_2 (m/s)	15	16.2	15	15.58	15.4
T_2 (°K)	322		314.5	320.2	325
ΔT	20	21.8	22	27	25
Δp_{tur} (Pa)	74	-	-	130.70	-
Δp_{poten} (Pa)	-	120	135	196.06	--
p_{load} (kW)	48	265MW/yea	48.3	123.59	--
η_{coll}	32%	35%	37%	43.58%	-
η_{ch}	0.65%	0.65%	0.65%	0.653%	-
η_{tur}	85%	85%	85%	85%	-
η_{tot}	0.176%	0.1934%	0.204%	0.242%	-

The result of the study shows, the solar chimney power plant improved by combining waste heat from another power plant. The model results of this study validated with the previous works and good result has been get with improved efficiency and greater power output.

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Figures

Figure 1

1. 1 Energy of collector roof

Figure 2

1. 2 Geometry of plant with heat source

Figure 3

3. 1 Annually Temperature Variation of Roof, Ground, Fluid Air and Pipe

Figure 4

3. 2 Daily Temperature Variation of Roof, Ground, Fluid Air and Pipe

Figure 5

3. 3 The Output Temperature of Fluid Air without Geothermal Water

Figure 6

3. 4 Temperature of Fluid Air at any Radius of Collector

Figure 7

3. 5 Static Pressure versus Radius of Collector

Figure 8

3. 6 Power Output versus Chimney Height and Collector Radius

Figure 9

3. 7 Velocity of Fluid Air versus Radius

Figure 10

3. 8 Efficiency of Plant with and Without Geothermal Power Plant