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Three Dimensional Modeling of Heat Extraction from Abandoned Oil Well for Application in Sugarcane Industry in Ahvaz– Southern Iran

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ABSTRACT

Abandoned oil and gas wells can be used as low temperature geothermal resources for heat extraction from geological formations and have valuable heat potential that avoids the cost increase of drilling in geothermal projects. Despite the industrial sectors that receives energy with subsidized price in Iran, but the cost of consumed fuel for most of industries such as sugarcane factories still is valuable and high. Khuzestan province in southern Iran is one of the richest areas in oil and gas resources and also is prominent in cane farms and sugar industry. However; the sugar mills are lagging due to power consumption. In this study the feasibility of steam generation as low geothermal resources from an abandoned oil well is investigated using a 3D simulation technique. The bottom-hole temperature of a well called DQ is 159.8°C. Heat transfer between fluid injected into the well and the surrounded hot rock was simulated. Well casing geometry for this well was considered and an exact geothermal gradient for each geological formation was applied. The simulation results were optimized for parameters such as input and output flow rates and temperatures. The results showed that, in addition to thermal gradient and mass flow rate, well casing geometry and the size of injection and extraction pipes were essential to the output heat extraction rate.

The simulation results are revealed, the extracted heat from underground which is combined with a gas furnace heater, has the ability to provide the required steam for a sugarcane factory near to Ahvaz City. In this case, the steam pressure and mass flow rate were 8 bar and 42 t/h, respectively. Also natural gas consumption and CO_2 emissions are reduced $2.7*10^6$ m^3/year and 5,042 t/year respectively. The average reduction of natural gas consumption is 17.3% compared to only steam boiler case. Return on Investment (ROI) in a geothermal-heater compared with a steam boiler at best case with pure interest rate of 8%, occurs after 3.6 years.

1. INTRODUCTION

Sugarcane is a very important product that in addition to sugar, also supplies raw materials. According to figure 1 about 43 percent of the Iran's sugar is supplied from sugarcane production between 2001 to 2013 and the rest is produced from sugar beet (Iranian Sugar Factories Syndicate, 2014). This contribution, due to the significant talent of the Ahvaz area in sugarcane cultivation can be increased. Total sugar production and sugar consumption in Iran in 2013 are equal to 1,124 and 2,200 thousand tones respectively and the excess consumption is supplied by imports (Iranian Sugar Factories Syndicate, 2014). But an import mechanism is not implemented, thus many companies are confronted with many problems. Firstly fuel consumption in the sugar producing industry in Iran is 4 times (790 lit/1 ton sugar) more than the international average rate and figure (Soleymani M. et al., 2011). On the other hand, low world sugar prices are making it increasingly difficult for raw sugar mills to remain competitive, and many milling companies in Iran are embarking on new revenue earning opportunities. It is essential to increase the economic viability of such projects by cost-effective reduction of the steam consumed by the factory. Due to the excessive consumption of fuel and rising energy prices in Iran for the industry in last 3 years, in addition to optimization of the sugar industry, they needed to replace the fossil fuel or supplying at least part of it by any renewable energy resources. Previously many researches have been conducted for increasing the efficiency, decreasing CO_2 emissions and application of renewable energy in sugarcane industry (Ensinas A.V. et al., 2007; García C.A. et al., 2011; Deshmukh R. et al., 2013).

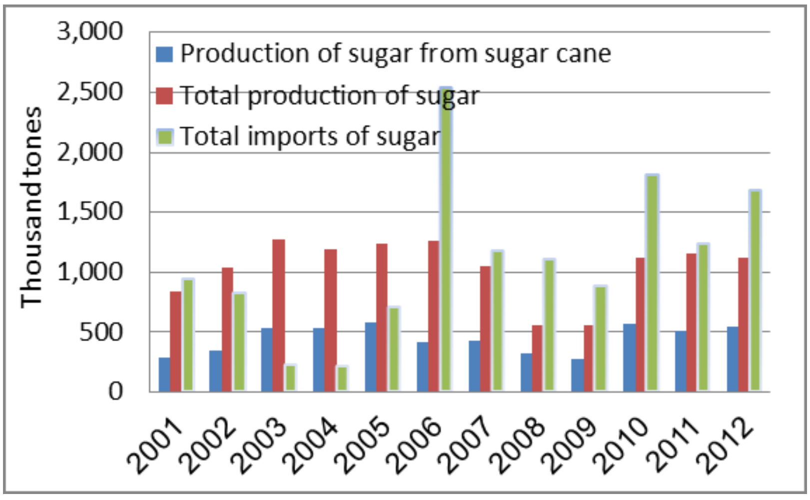

Figure 1: Production of sugar from sugar cane, total sugar production in Iran and the total sugar imports to Iran

In Ahvaz, there are so many abandoned oil wells that could be used as geothermal wells and they can be used as low temperature geothermal energy in order to provide steam for the sugarcane factories. Geothermal energy is a commercially proven renewable form of energy which can provide relatively cheap, low-carbon, base-load power and heat that can reduce dependence on fossil fuels and lower CO_2 emissions with high reliability (Gehringer M. and Loksha V., 2012). Low-temperature (100–150°C) geothermal heat sources are valuable potential sources of renewable energy (Tester J. et al., 2006). Research on this major source of energy can increase the applicability of renewable resources (Noorollahi Y. and Itoi R., 2011). An innovative method is the extraction of heat from abandoned oil and gas wells as a renewable energy source. There are significant numbers of abandoned oil and gas wells around the world and in Iran. If these abandoned wells could be used as heat sources to extract geothermal energy, they could provide low cost heat by eliminating the cost of drilling, avoiding environmental problems associated with accidental spillage by using existing oil fields.

Several studies have been done on the utilization of abandoned wells as geothermal wells, (Kujawa T. et al., 2006; Davis A.P. and Michaelides E.E., 2009; Bu X. et al, 2012; Cheng W.L. et al., 2013), but no studies have been conducted to analyze heat transfer between rock and fluid in wells using 3D modeling of an actual abandoned oil well by considering the actual geothermal gradient and simulating the exact well geometry and thickness of the ground layers (Pourarshad M. et al, 2014). These conditions increase the accuracy of the calculations and the precision of heat and power extraction. The present study simulated abandoned oil well in the Ahvaz oil field in southern Iran and evaluated the effects of the geothermal gradient and mass flow rate on fluid outlet temperature. A feasibility study for producing steam from hot fluid extracted from a well in a gas furnace heater was examined. Amount of savings in natural gas consumption and reduction in CO_2 emissions for this proposed model (Geothermal combined gas furnace heater) in comparison to a steam boiler to produce steam for the same conditions required by the sugar factory has also been achieved. At the end, the initial investment and the return on investment is calculated.

2. PHYSICAL MODELS AND INPUT DATA

The techniques for heat extraction from abandoned oil and gas wells are different from conventional geothermal systems. The circulating fluid is not in direct contact with the hot rocks. The fluid circulates in a coaxial double-pipe heat exchanger and heat transfer occurs without mass transfer. The fluid circulates in the well by means of a concentric double pipe. Cold water is injected into the well through the outer pipe and the heat transfers from the hot rock to the fluid during injection, heating the fluid. The hot fluid is rises up through the inner pipe and is extracted. To avoid heat transfer between the outer and inner pipes, extruded polystyrene thermal insulation surrounds the inner pipe. The abandoned oil well (DQ) modeled in this study is located in Ahwaz city in southern Iran. Well specifications, casings, and diagrams of a proposed double-pipe heat exchanger are shown in Figure 2 and other specifications of the well and the model of heat exchanger (DQ-II) are presented in Pourarshad M. et al. (2014).

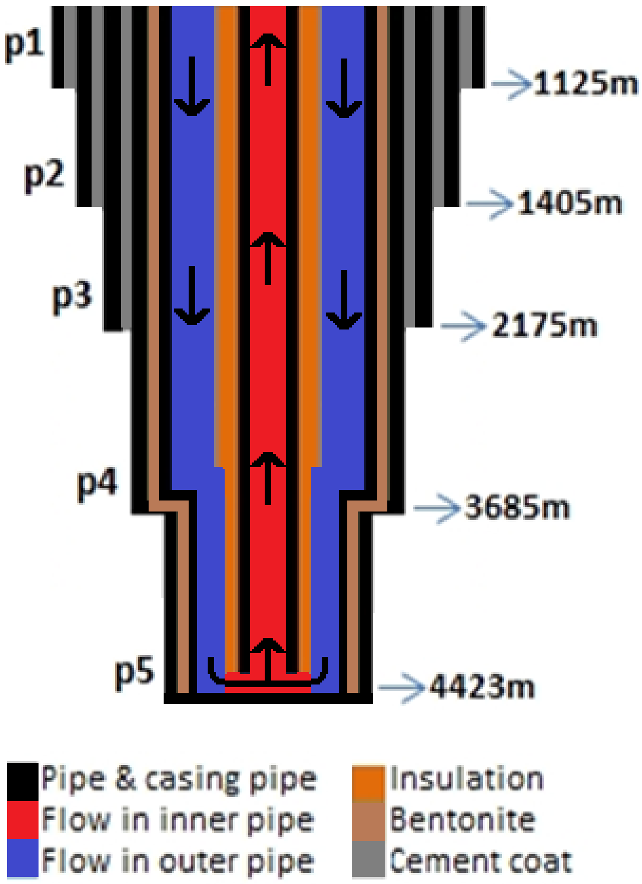

Figure 2: Schematic representation of well casing and a double-pipe heat exchanger for well DQ.

The depth of well DQ is 4,423 m. The diameter of the casing pipe at ground level is 20 inches and narrows to 7 5/8 inches at the final depth. A model of the coaxial pipe heat exchanger was designed for well and is shown in Figure 2. All oil well casings are stainless steel and the area between the oil well casing and the outer pipe is filled with bentonite clay material. The circulating fluid in the wells is water. The geothermal gradient of the well is shown in Figure 3. As seen in the thermal profile, it follows the conduction heat transfer method for both wells. The bottom-hole temperature for DQ is 159.8°C. The temperature gradient was 31.2°C/km, which corresponds to the world average thermal gradient. In the computation model, the exact temperature for each geological layer was applied using the measured temperature gradient. The ground layers in oil well were considered precisely and the thermo-physical properties of the geological layers were applied (Emirov S.N. and Ramazanova E.N., 2007; Asaad Y., 1955).

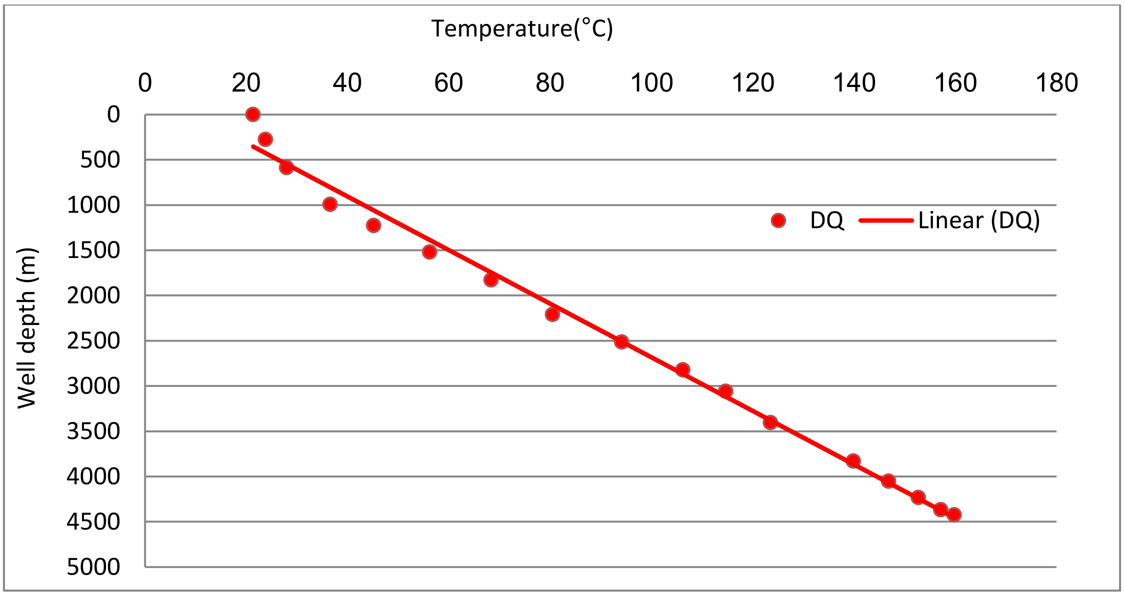

Figure 3: Geothermal temperature change with depth

The examined sugarcane factory intended for the study requires about 42 t/h steam with 8 bar pressure that is supplied by two steam boilers with a thermal efficiency of 85%. In this proposed method, in order to produce the consumed steam from the fossil fueled boiler, a hot fluid outlet from an abandoned oil well is inserted into a gas furnace heater. Unlike the steam boiler, gas furnace heater turns the hot water extracted from the well into steam. In this process, lower energy is used for generating steam which finally results in reduction of fuel consumption.

3. SIMULATION MODEL

3.1. Simulation of downhole heat exchanger

A 3D model of the oil well casings and meshing geometry was constructed using ANSYS Design Modeler. A Cartesian coordinate system was selected for all well components. The sectional area of each component was designed in the XY plane according to their depths, then all sections were extruded into the +Z direction according to their lengths. Figure 4 shows an internal cutting of geometrical primitives where the quality of injection and extraction of flow is shown.

Figure 5 presents the grid topology used for the three-dimensional grid system. In the meshing tools, the physical preferences and meshing method were selected using computational fluid dynamics and the multi-zone method. The mapped mesh type was hexa/prism and the relevance center was medium. The specifications of generated mesh are shown in Table 1.

Table 1: Information about meshing generation

model	Number of grid	Number of nodes	Aspect ratio
DQ-II	1,934,156	1,968,549	81.66

Simulation model was carried out using ANSYS Fluent software. The pressure-based solver method was selected because of the low speed and incompressible flow. The conservation equations for this model were energy, momentum and continuity, which were chosen to obtain the governing equations for the Fluent energy and viscosity models (ANSYS FLUENT Tutorial Guide, 2011).

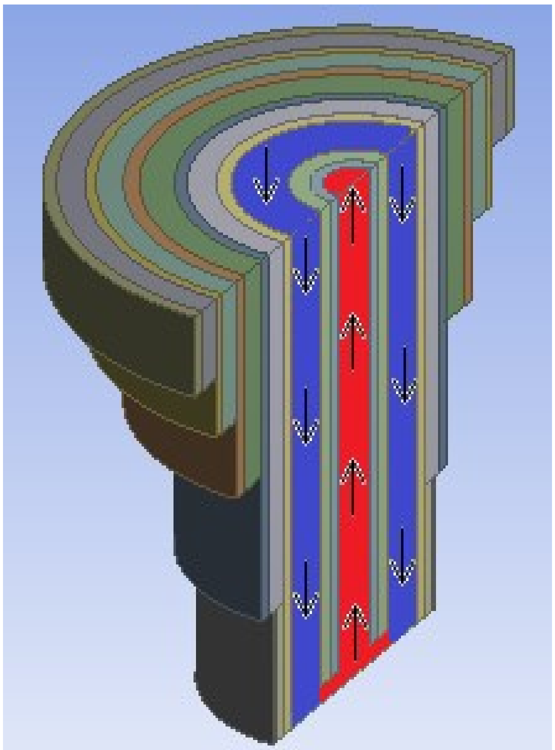

Figure 4: Schematic of initial internal cutting of well and heat exchanger geometry

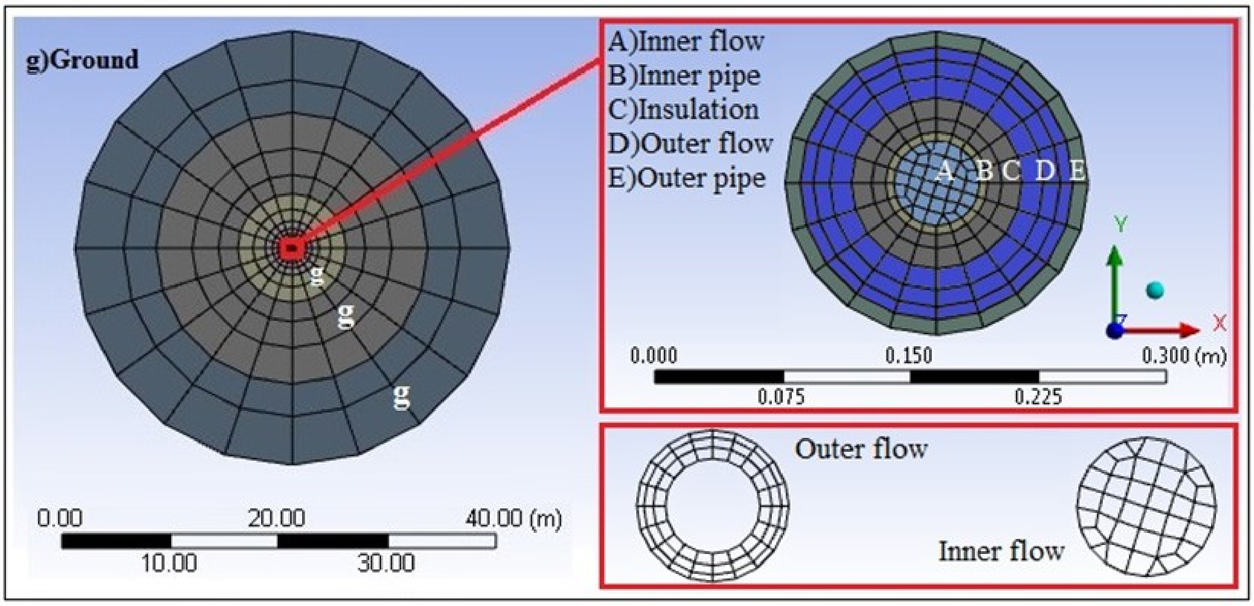

Figure 5: Schematic representation of meshing geometry

The general equation for conservation of mass (continuity equation) is as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = S_m \quad (1)$$

Source S_m is the mass added to the continuous phase from the dispersed second phase and any user-defined sources; ρ and $\vec{v}$ are the density and overall velocity vector, respectively.

The Conservation of momentum is described as:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.\bar{\bar{\tau}} + \rho \vec{g} + \vec{F} \quad (2)$$

Where p is the static pressure, $\bar{\bar{\tau}}$ is the stress tensor, and $\rho\vec{g}$ and $\vec{F}$ are the gravitational body force and external body force, respectively. Stress tensor $\bar{\bar{\tau}}$ is:

$$\bar{\bar{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^T) - \frac{2}{3}\nabla.\vec{v}I\right] \tag{3}$$

Where μ is the molecular viscosity, I is the unit tensor, and the second term on the right-hand side is the effect of volume dilation.

The energy equation is solved as follows:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left(\vec{v}(\rho E + p)\right) = \nabla.\left(K_{eff}\nabla T - \sum_j h_j\vec{J}_j + \left(\bar{\bar{\tau}}_{eff}.\vec{v}\right)\right) + S_h \tag{4}$$

Where K_{eff} is the effective conductivity and $\vec{J}_j$ is the diffusion flux of species j. The first three terms on the right-hand side of Equation 4 represent energy transfer from conduction, species diffusion, and viscous dissipation, respectively. S_h is the heat of the chemical reaction, and any other user-defined volumetric heat sources.

In Equation 4, E is the total energy and can be defined as:

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{5}$$

Where sensible enthalpy h is defined for incompressible flows as:

$$h = \sum_j Y_j h_j + \frac{p}{\rho} \tag{6}$$

In Equation 6, Y_j is the mass fraction of species j and:

$$h_j = \int_{T_{ref}}^{T} C_{p,j}\, dT \tag{7}$$

Where $C_{p,j}$ is the heat capacity at constant pressure of species j.

In the solid region, the internal energy transport equation without considering fluid flow takes the following form:

$$\frac{\partial}{\partial t}(\rho h) = \nabla.(K\nabla T) + S_h \tag{8}$$

Where, for:

$$h = \int_{T_{ref}}^{T} C_p\, dT \tag{9}$$

And T_{ref} is 298.15 K for the pressure-based solver.

For the viscosity equation in this model, parameters can be defined as inviscid, laminar, and turbulent flow. By calculating the Reynolds number according to Equation 10, the realizable K-Ɛ model was selected:

$$Re = \frac{\rho v d_h}{\mu} \tag{10}$$

Where d_h is the hydraulic diameter. For the injection and extraction wells, it is calculated as:

$$d_{h,injection} = 2\sqrt{(R^2 - (r_2 + t)^2)} \tag{11}$$

$$d_{h,extraction} = 2r_1 \tag{12}$$

Where R is the inner radius of the injection well, t is the insulation thickness, and r_1 and r_2 are the inner and outer radii, respectively, of the extraction well.

The turbulence intensity is defined as the ratio of the root-mean-square of velocity fluctuation u' to mean flow velocity u_{avg}. The turbulence intensity can be calculated using the Reynolds number as:

$$\bar{I} = \frac{u'}{u_{avg}} = 0.16(Re_{d_h})^{-1/8} \tag{13}$$

3.2. Hybrid steam providing (Downhole heat exchanger and gas-furnace heater)

In the second part of the simulation, the results from the first part (well simulation output) were used as input to simulate the designed gas furnace heater using Cycle-tempo software. Thermal power consumed by the gas furnace heater (Figure 6) for each change in mass flow rate was calculated. Then based on power consumption, amount of fuel required is calculated and the difference in fuel consumption between the geothermal with heater and boiler will be seen. Also, to calculate the amount of reduced CO_2 emissions, the RETscreen software was applied.

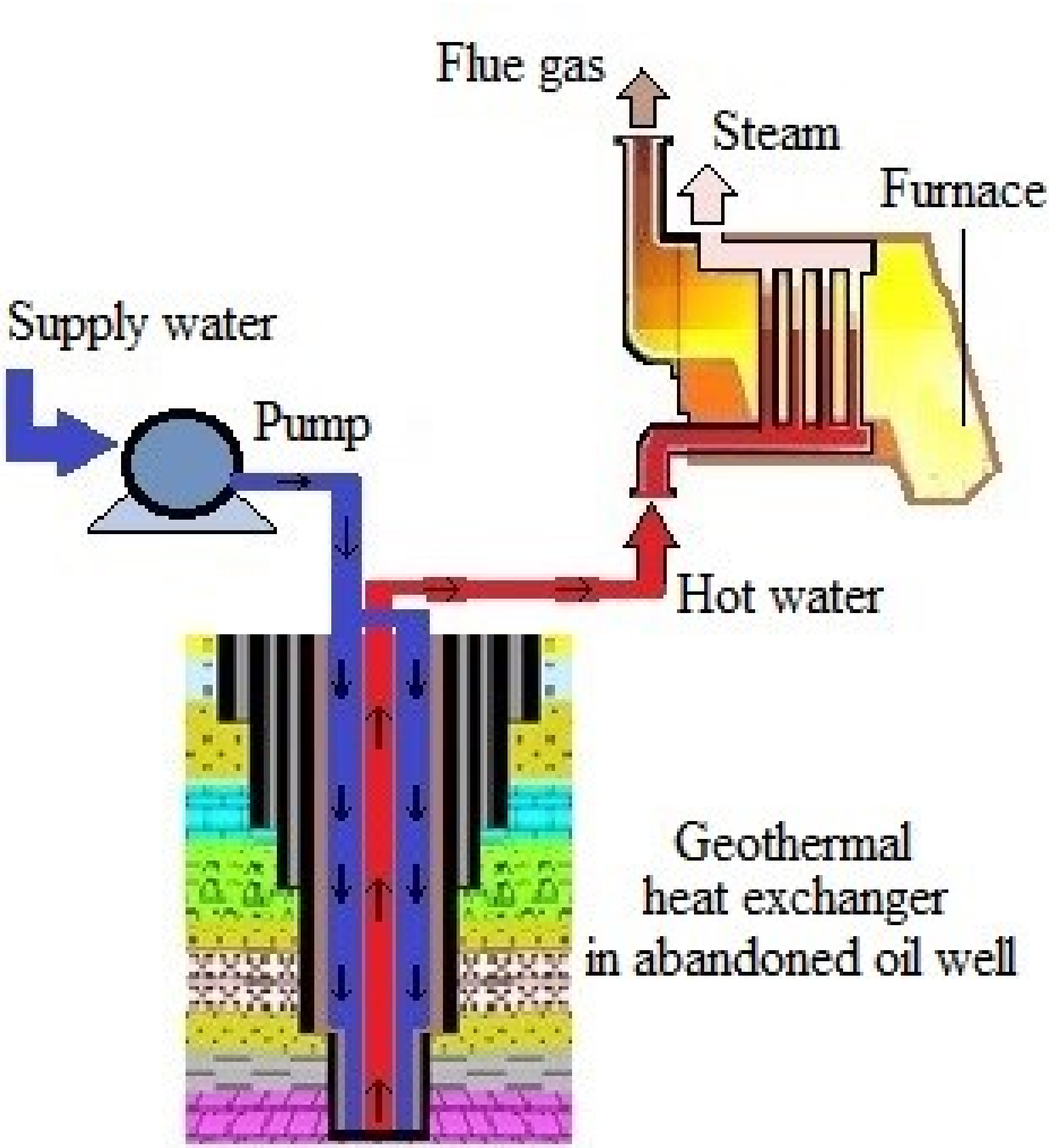

Figure 6: Schematic of combined geothermal heat exchanger and gas furnace heater

4. RESULTS AND DISCUSSION

In the downhole simulation run, inlet velocity and outlet pressure were selected to define the boundary conditions for the inlet and outlet zones. For all ground layer zones, the wall type was so that the wall temperature was based on the well temperature gradient (Figure 3). Calculation begins after computing all zones in solution initialization for well model. In the next step, data are presented for the gas furnace heater and for each mass flow rate, the required thermal power and fuel consumption are calculated. Other effective parameters applied in the computation are shown in Table 2.

Table 2: Parameters used in simulation

Temperature of the water entering the well	30 °C
Velocity of the water entering the well	$0.2m/s < v < 0.8m/s$
Pressure of extracted water of the well	8.5 bar
Stainless steel roughness (Moody L.F.,1994)	0.015 mm
Pump efficiency	82%
Gas furnace heater thermal efficiency	85%
Steam boiler thermal efficiency	85%
Heating value of natural gas	38.4 MJ/m^3
Average fuel consumption in steam boiler for generating a ton of steam per hour	77 m^3/h

Figure 7 shows the bottom-hole fluid temperatures and the outlet fluid temperature at different mass flow rates. With enhanced inlet velocity, fluid temperature lost in extraction pipe is low and the outlet fluid temperature is closer to the bottom-hole fluid temperature. The equations used to calculate the thermal resistance of the heat transfer was provided by Incropera F.P. et al., (2007). As inlet velocity increased, the mass flow rate increased and decreased the fluid temperature at the bottom of the well. The maximum fluid temperature at the bottom of the well with an inlet velocity of 0.21 m/s and a mass flow rate of 3.49 kg/s was 153.6°C. Outlet temperature, unlike the fluid temperature at the bottom of the well, has an optimal value. The maximum outlet temperature from the well was 141.4°C for a mass flow rate of 4.76 kg/s. Mass flow rate out of the well in order to provide steam for the factory at a rate of 42t/h is 11.9 kg/s with a temperature of 133.9°C and a pressure of 8.5 bar.

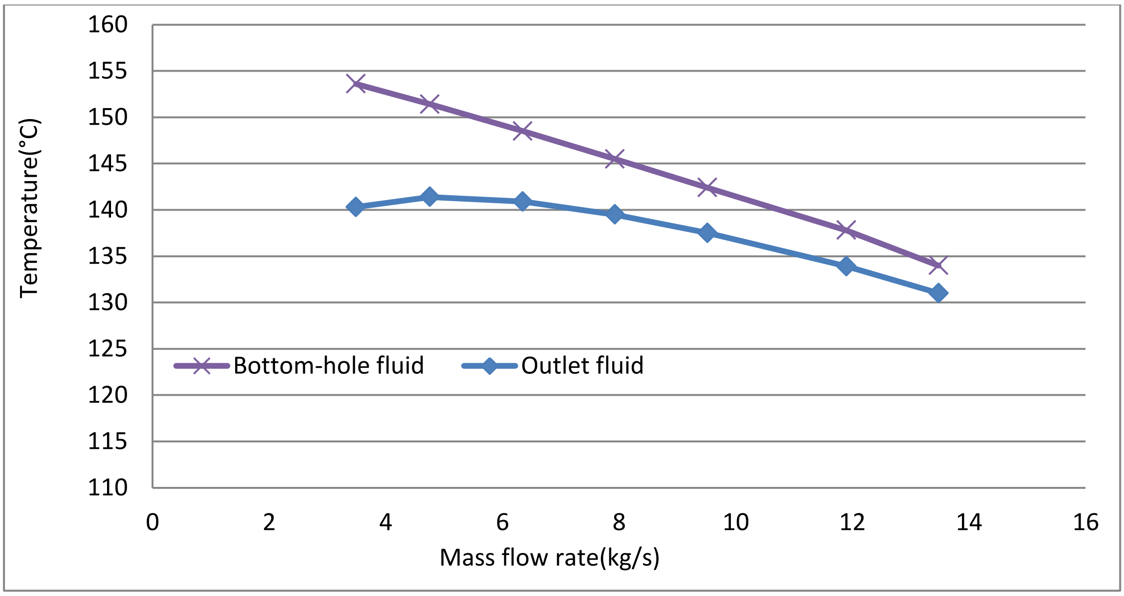

Figure 7: Bottom-hole fluid and outlet temperature changes with mass flow rate of water

Figure 8 shows a comparison of heat power consumption for steam production between steam boiler and the heater combined with geothermal systems. As it can be seen, power consumption is lower in the hybrid system. The reason of this reduction is that the extraction hot water from the well is converted to steam in heater, while in the steam boiler cold water is converted to steam. With the rising of steam mass rates, the difference in power consumption is further and the reason is the increased thermal energy extraction from the well which results in reduction of heater power consumption.

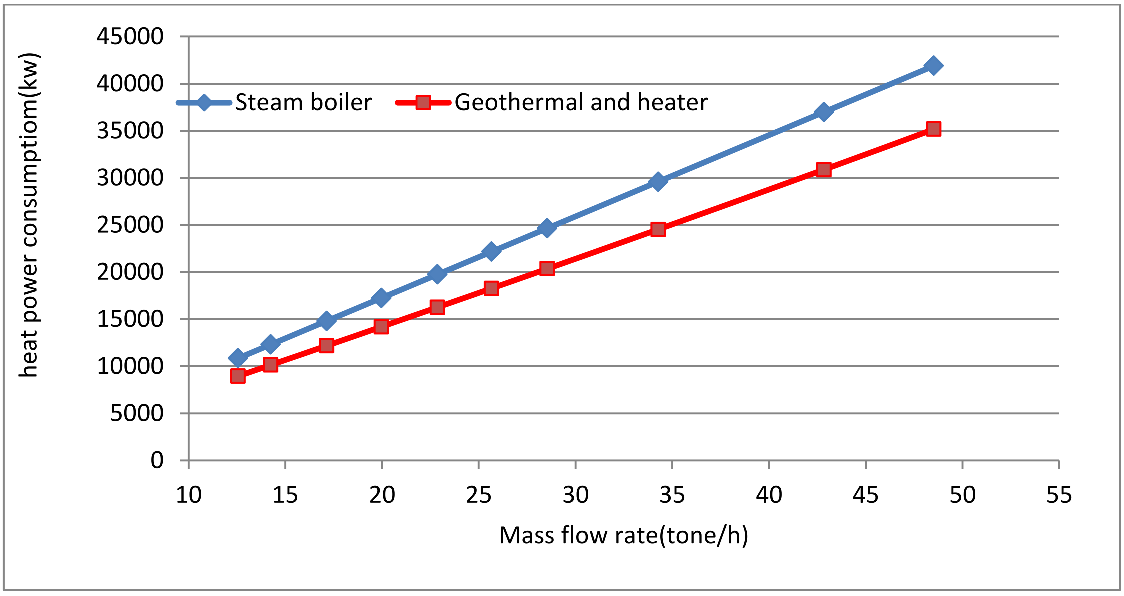

Figure 8: heat power consumption changes with mass flow rate of steam

In the Figure 9, the rate of fuel savings by combining geothermal and gas furnace heather are shown. Average reduction in fuel consumption is 16.5% that is equal to 42.8 tons of steam per hour. Power consumption for producing this amount of steam for steam boiler and hybrid system is equal 36.9 MW and 30.8 MW respectively. This result indicates that in order to produce 42 t/h of steam, 545 m^3/h of natural gas will be saved. However, the difference in energy consumption between the boiler and hybrid system rises with mass rates increasing. The ratio between them initially increases and then decrease. Maximum fuel savings is equal to 17.8% for 17 t/h of steam. According to Figure 9, the amount of fuel savings decreases by increasing mass flow rates. It is because of reducing the outlet fluid temperature from well. The outlet fluid with a lower temperature from the well leads to higher gas consumption in combined hybrid system.

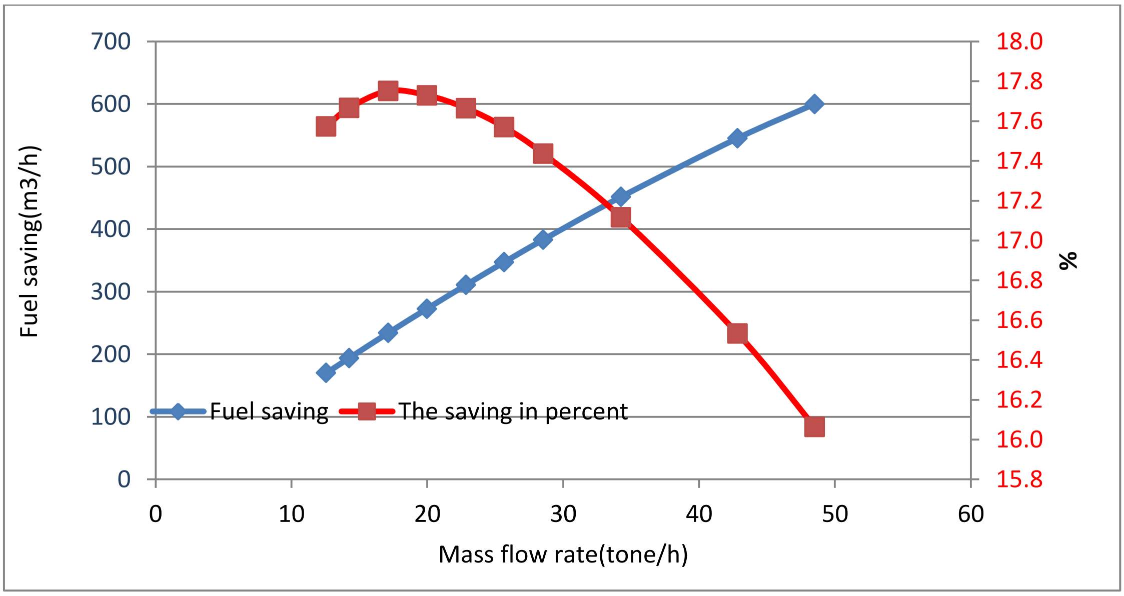

Figure 9: Fuel saving changes with mass flow rate of steam

In Table 3, the sugarcane factory operating hours and other economic data are given. For this activity level the amount of savings in natural gas consumption and CO_2 emissions reduction at each rate of required steam are calculated and shown in Figure 10. For the required supply of 42 t/h steam that is produced by hybrid system is 2,705,000 m^3/y of fuel will be saved that is equal to 5,042 t/y reduction of CO_2 emissions.

Table 3: Factory operating hours and other economic data project

Operating hours per year	4960 hours
Natural gas price for industry	7 cents
Average price of electricity for industry	13 cents
The initial cost of drilling and preparation of wells	0 $
Initial cost of downhole heat exchanger	337,500$
Initial cost for changing the system to produce steam by gas furnace heater	24,100 $
The total investment cost	361,600$
Return on investment rate	8%

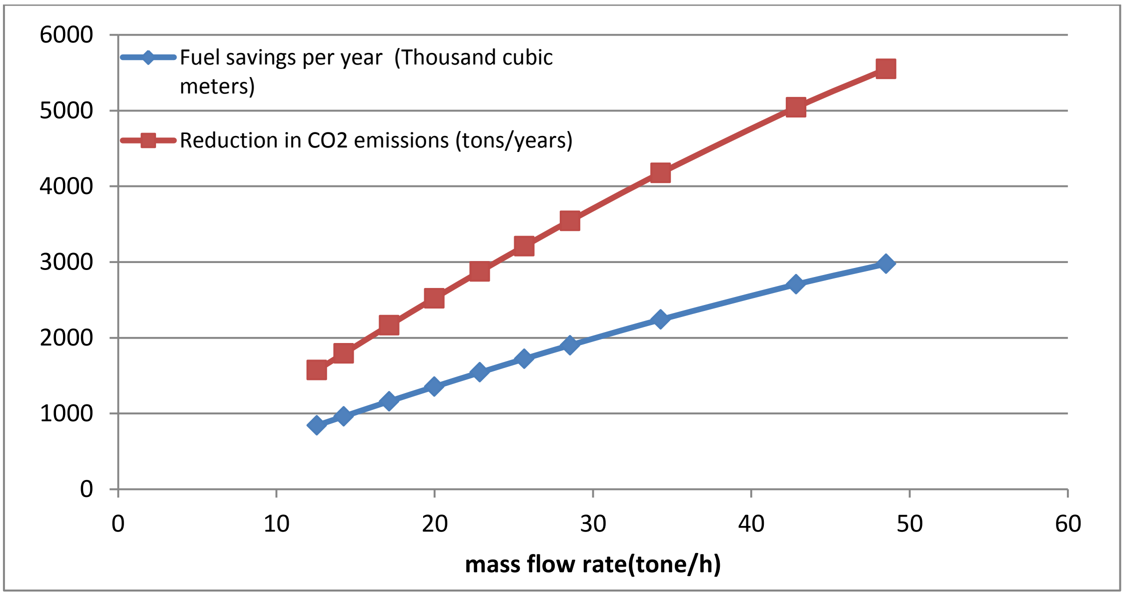

Figure 10: Fuel saving and reduction of CO_2 emissions changes with mass flow rate of steam

Economically, the project will also lead to the reduction of savings in current costs. However, the hybrid system needs to be charged more for electricity (power consumption for pumping fluid for extraction hot water), the reduction in supply of fuel costs outweighs it. Figure 11 shows the excess of the cost of electricity that is more in geothermal pumps rather than steam boilers, savings in supply of fuel costs and income from implementation of the project per year. For 42 t/h of steam, annual income is equal to $119,046 that with a return on investment of 8%, after 3.6 years, the initial investment will be returned. It should be noted that as the fuel price closes to the international price, income will significantly increase and the payback time will be reduced. Also the use of geothermal energy from abandoned oil well has no drilling cost and it is one of the most important factors in investment attractiveness.

5. VALIDATION OF SIMULATION

To determine the validity of the results of this study, it was compared with the results of other studies. The accuracy of the results of well DQ were compared with those from Cheng W.L. et al. (2013). In Cheng W.L. et al., the depth of the well was 6,000 m, the diameter of the injection pipe was 28.25 cm, and the pipe thickness was 1.5 cm. The external diameter of the extraction pipe was 12 cm and the geothermal gradient was 40°C/km. The circulating fluid in the well in Cheng W.L. et al. was isobutene. The results are summarized in Table 4 and show that the output of DQ is comparable to the results of the previous study. In previous studies, the ground properties were assumed to be similar and constant at all well depths, the temperature gradients were expected to be constant at all well depths, and the inner and outer pipe diameters were not subject to actual oil well conditions. While in the simulation of this study all items are listed standard and detailed as already mentioned. Above all redesigning and improving the heat exchanger in this model achieved better results for generation heat from DQ-II well. Also the amount of reduction of CO_2 emissions for production of 42t/h of steam was achieved 5,042t/y and this amount is 5,071t/y with using the method of Aubé F. (2001). By comparing both numbers, it can be seen that the results are acceptable.

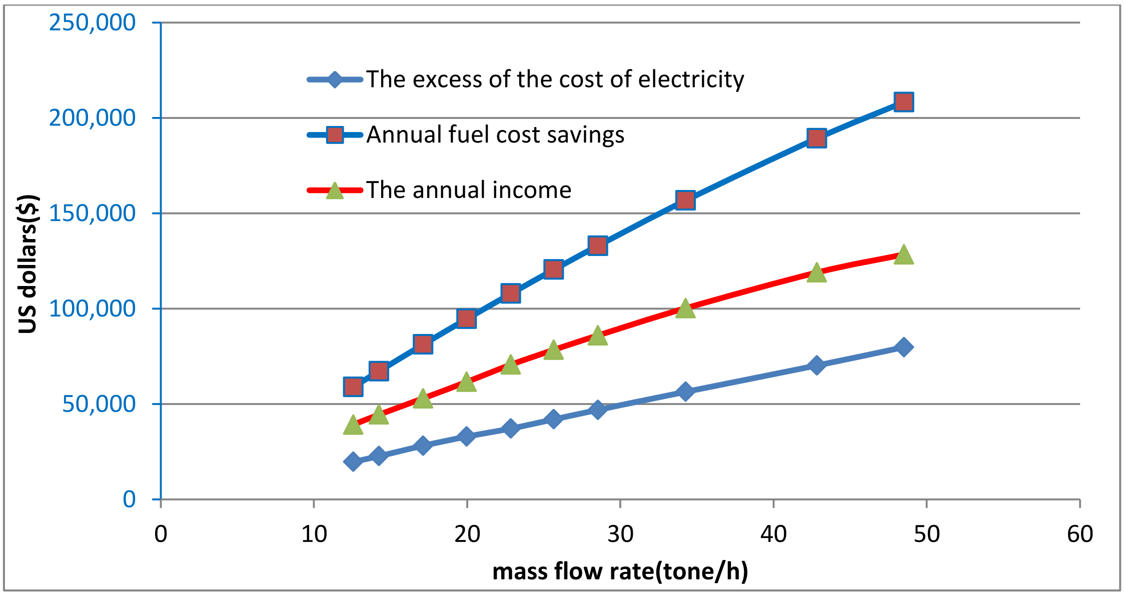

Figure 11: The economic condition changes with mass flow rate of steam

Table 4: Comparison of simulation results with results of Cheng W.L. et al.(2013)

Model	Bottom hole Temperature (°C)	Outlet temperature(°C)	Flow rate	Total obtained heat from well (kW)
Cheng W.L. et al.(2013)	240	136.1	0.18 m/s	1201
DQ-II	159.8	137.8	11.9 kg/s	1842

6. CONCLUSIONS

The present study investigated 3D simulations of abandoned oil wells and the governing equations of heat transfer were applied for simulation. Using the results of well simulation output, the amount of reduction for fuel consumption and reduction of CO_2 emissions in gas furnace heater was investigated. The geometry of the actual oil wells, ground layer properties and temperature gradients at each layer of the earth were entered as simulation input. The results show that, in addition to the temperature gradient and mass flow rate, well casing geometry had a large impact on heat transfer in the wells and on final steam production. Injection pipe design with two different sizes in an oil well has three advantages. One advantage is a higher mass flow rate allowed by the larger diameter of the outer pipe and another advantage is the increase in temperature of the outlet fluid from the well with the decrease in thermal resistance and increase in insulation thickness. A third advantage is lower fluid pressure in the injection to the well because of the larger diameter of the inner pipe.

The merit of a hybrid geothermal and gas furnace heater for generation of 42 t/h of steam for a sugarcane factory are reduction of natural gas consumption to 2,705,000 m^3/y and reduction of CO_2 emissions about 5,042 t/y. Due to the absence of drilling and well preparation cost, the initial investment cost is just the cost of the heat exchanger inside the well and switch the boiler to heater in order to generate steam. With these conditions, annual saving is $119,046 which with the rate of return on investment is 8%, it takes 3.6 years to return to the capital.

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