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Thermal Energy Estimation by In-situ Combustion in An Abandoned Oil Well

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Abstract

A downside of producing oil is that it can never be fully recovered. After the end of a well's life span, the residual oil remaining in the reservoir on average can be over 30%. This residual oil can be extracted using enhanced oil recovery techniques, one of which combusts the oil in the formation where the average reservoir temperature can increase to 400ºC for light oil and over 600ºC for heavy oils. This method can become a significant catalyst in solving Pakistan's energy need and increasing power production. This paper aims to estimate the thermal energy production by combusting this residual oil using in-situ combustion by air injection technique. The study deals with the well Kahi-01 located in the upper Indus basin having three formations. The main target is the Hangu formation and its three reservoir blocks. This formation is characterized by its high residual oil percentage of 76-85% at depths of about 1691-1741 meters. The results show that the highest thermal energy output among the three reservoirs was $34.6e^6$ Megajoules. The highest power output from the binary plant was $38.5e^4$ Kilowatt hour.

INTRODUCTION

Challenges in meeting Pakistan's energy demands and combatting greenhouse gasses' excessive emission is a significant issue in Pakistan's energy scenario. The overall energy scenario in Pakistan depends on fossil fuel. The energy demands exceed the supply (Shakeel et al., 2016). In 2014-15, Pakistan's greenhouse gas emissions were 405 mega tonnes equivalent of CO_2, projected to increase to 898 mega tonnes of CO_2 equivalent (Ur Rehman et al., 2019).

After being abandoned, most oil wells still possess some quantity of residual oil, which varies depending on well conditions. This residual oil can be combusted to generate heat energy which in turn can generate power. Pakistan has about 1000 exploratory wells drilled. Around 60 % of them have been abandoned due to lack of resources or plugged after extracting the maximum extractable amount of hydrocarbons (Mehmood et al., 2017). For this study, the in-situ combustion technique is utilized, which can extract heat from the reservoir block right at the initiation of the process, therefore; shortening the payback period (Zhu et al., 2019).

Around $2.0e^{12}$ barrels of light oil and $5.0e^{12}$ barrels of heavy oil remains in the reservoir worldwide after conventional recovery methods have been exhausted. This remaining oil can be recovered by enhancing oil recovery, which is a part of a broader general classification of 'improved oil recovery (IOR)'. Generally, the method of EOR used is dependent on the particular characteristics of the reservoir (Thomas, 2008).

Several methods of EOR used, namely, thermal methods, steam flooding, gravity drainage and in-situ combustion (Ferizal et al., 2013; Hidayat & Abdurrahman, 2018; Kusumastuti et al., 2019; Melysa, 2016; Thomas, 2008). The paper's scope deals with the in-situ combustion method; hence, this will be discussed thoroughly.

The EOR process applied in this study is in-situ combustion. Hot water, gas or steam is injected into the well, which then reacts with the residual oil. Then combusts it and produces lighter hydrocarbons and coke after a series of a complex physical and chemical process. This complex procedure is divided into

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three stages; Low-temperature oxidation (LTO), medium temperature oxidation (MTO) and high-temperature oxidation (HTO) (Yuan et al., 2019).

Based on current research, the oil reservoir temperature could reach over 400ºC for light oil and 600ºC for heavy oil reservoirs. The efficiency of power generation through in-situ combustion is significantly higher than that by producing geo-fluids from the well (Li & Zhang, 2008). The generated heat energy can then be converted into power by using a binary powerplant or another type of plant.

Low-Temperature Oxidation (LTO).

There are two steps in LTO. Stage one is injecting hot air into the residual oil and allowing it to react with the crude. Step two is the heavy oil's three-stage combustion, which produces high-temperature thermal energy in the reservoir block. LTO happens in the initial stages of injection. It help produces partially oxygenated compounds such as aldehydes, ketones, and alcohols. This partial oxidation changes the crude oil state that is important for the oil's mobility (Nemati Zadeh Haghighi et al., 2019).

Medium-Temperature Oxidation (MTO).

The next stage is the MTO. This stage includes distillation, molecule breaking and coke formation as the crude oil flows from the initial reaction. In this stage, the crude molecules undergo further oxidation and release heat. A portion of the heavy oil is converted into light oil (LIAO et al., 2020).

High-Temperature Oxidation (HTO).

The final stage, the HTO, is the most critical. It involves the oxidation of the cracked hydrocarbon residue formed in the previous stages. In HTO, the main products from oxidation are fully oxidized CO_2 and CO (Li & Zhang, 2008). For heavy oils, the results of HTO are more pronounced as compare to light oils. This stage's average activation energy is much larger than LTO and MTO (Nemati Zadeh Haghighi et al., 2019).

Table 1. Reaction stages of residual oil

Stage	Temperature (ºC)	Peak Temperature (ºC)
LTO	40-387	340
MTO	387-426	--
HTO	426-600	531

Reaction stages of residual oil can be seen in Table 1. The following reactions summarize the reactions involved in in-situ combustion (Hart, 2014).

Pyrolysis reaction.

$$\text{Heavy residual oil} \rightarrow \text{Light oil} + \text{coke} \tag{1}$$

Oxidation of coke.

$$C + O_2 \rightarrow CO + CO_2 + H_2O \tag{2}$$

Oxidation of heavy residual oil.

$$\text{Heavy residual oil} + O_2 \rightarrow CO + CO_2 + H_2O \tag{3}$$

The final step uses a production well to produce the heat energy, pass it to a heat exchanger and then utilize it to generate power.

MATERIALS AND METHODS

Geological Setting.

This research conducts on an abandoned well, the Kahi-01, located in the upper Indus Basin, as shown in Figure 1. Three formations are encountered in the Kahi-01 well; Lockhart Limestone, Hangu Sandstone and Lumshiwal formation (See Figure 2). From these formations, Hangu has three potential reservoir zones; A_1, A_2 and A_3. The three reservoirs' properties are stated below in Table 2 (Saddique et al., 2016).

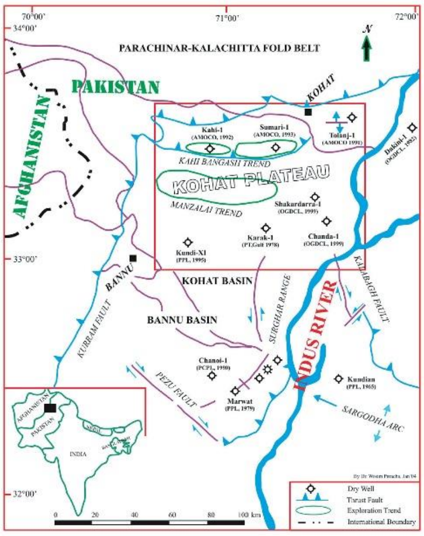

Figure 1. Location of Kahi-01 well along with geological trends (Paracha, 2004).

This paper focuses on the reservoirs of the Hangu formation, which ranges from 1691-1741 meters. The reservoir is assumed to be a two-phase reservoir containing only oil and water.

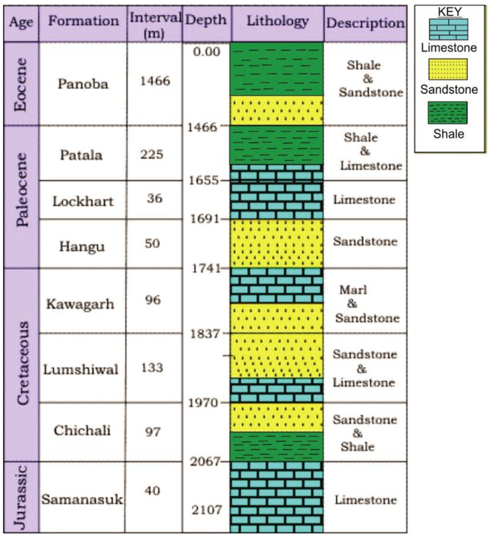

Figure 2. Stratigraphic section of the Kahi-01 well (Saddique et al., 2016).

The Moris Biggs determines the permeability in equation 4 (Mulyanto et al., 2020).

$$k = 62500((eff\,\%)^6/(Sw)^2) \tag{4}$$

Table 2. Reservoir specifications (Saddique et al., 2016).

Zone	Thickness (m)	Porosity (%)	Hydrocarbon Saturation (%)	Water Saturation (%)	Effective Porosity (%)	Permeability (mD)
A_1	7	5.5	76	24	3.4	167622
A_2	15	6.4	82	18	5.5	5339629
A_3	22	9	86	14	6.8	31526620

In-situ Combustion Mechanism.

Well Specifications.

In this study, a U-tube closed loop is used for the production well, which carries the heat from the reservoir to the surface. At the surface, the heat is absorbed by the heat exchanger from the fluid. The fluid is returned for another cycle, as illustrated in Figure 3. From the heat exchanger, the thermal energy can then be fed into a power plant. In our case, a binary power plant is utilized in which a turbine is used to generate power.

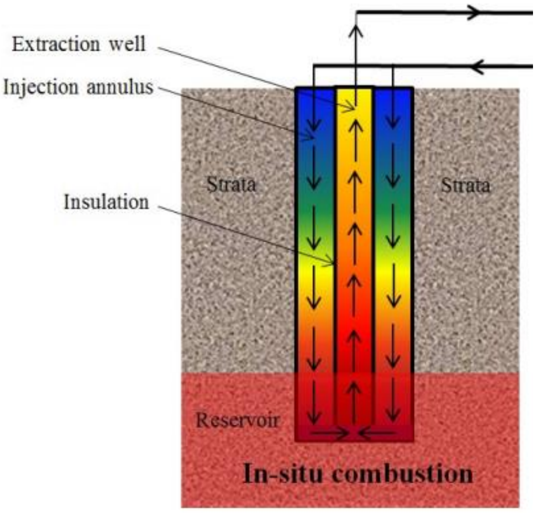

Figure 3. Schematic of the heat exchange system created in the well (Tian et al., 2018).

Working

The hot oxygen-enriched air is pumped into the injection well. This hot air reacts with the heavy residual oil to combust it and produce lighter fractions and heat energy. The thermal energy produced is given by the following equations (Li & Zhang, 2008).

$$V_o = A\ H\ \varphi\ S_{or} \qquad (5)$$

The amount of heat generated in the reservoir is given by (Li & Zhang, 2008).

$$Q = m\ q \qquad (6)$$

$$m = V_o\ \rho_o \qquad (7)$$

$$Q = \rho_o\ A\ H\ \varphi\ S_{or}\ q \qquad (8)$$

The average value of crude density is around 950 Kg/m^3, while the calorific value is 40 MJ/Kg.

The total heat energy produced in the reservoir cannot be fully utilized as a major part of that heat is lost to the surrounding formations (Hart, 2014). Assuming that 20% of that heat generated can be recovered from the well. The total thermal energy is reduced to (Li & Zhang, 2008);

$$Q_o = Q\ 0.2 \qquad (9)$$

A U-tube stainless steel pipe with a roughness of 0.00025 is used in the production well to extract the heat. Water is circulated in the well to produce the thermal energy in a closed-loop system and deliver it to the heat exchanger.

The stream from the heat exchanger is fed into a binary power plant with 20% efficiency. Therefore, the total power generated from thermal energy can be obtained, shown by equation (10) (Li & Zhang, 2008).

$$P = Q_o\ 0.2 \qquad (10)$$

Pressure loss.

The pressure loss in the closed-loop U-tube pipe is calculated using the Darcy-Weisbach equation (Srivastava & Teodoriu, 2018).

$$\Delta P = f_D\ L\ (\rho/2)\ (v^2/D) \qquad (11)$$

To calculate the Darcy friction factor, the following equation is used (Kiijarvi, 2011).

$$f_D = 0.316/(Re^{0.25}) \qquad (12)$$

Reynold's number is attained from the below equation (Røksland et al., 2017).

$$R_e = \rho v D/\mu \qquad (13)$$

Where the velocity is calculated by,

$$v = 1.273\ V/D^2 \qquad (14)$$

The diameter of the tubing is $2^5/_8$ inches. The working fluid is water, the density of which is 991 Kg/m^{3,} and the viscosity of is 0.000315 Pa-sec.

RESULTS AND DISCUSSIONS

In this study, the heat transfer and pressure loss characteristics are determined for an abandoned oil well. The well, Kahi-01, located in the upper Indus basin, has an extremely high residual oil saturation ranging from 75 to 85%. The well's parameters were utilized to make a theoretical estimation of the amount of thermal energy generated.

The outcome of this study, as seen in Figure 4, establishes that the reservoir block A_3 — which has the highest residual oil saturation and thickness— produces the most considerable amount of thermal energy around 8.6e^6 to 34.6e^6 MJ. The highest amount of power of 38.5e^4 Kilowatt hour. Similarly, block A_2 produces around 2.7e^6 to 10.9e^6 MJ of thermal energy and block A_1 generates 0.4e^6 to 1.8e^6 MJ of thermal energy. However, it should be considered that a small binary power plant cannot utilize such large amounts of heat. For that reason, it should be noted that the most economical outcome will be achieved from block A_1 and A_2.

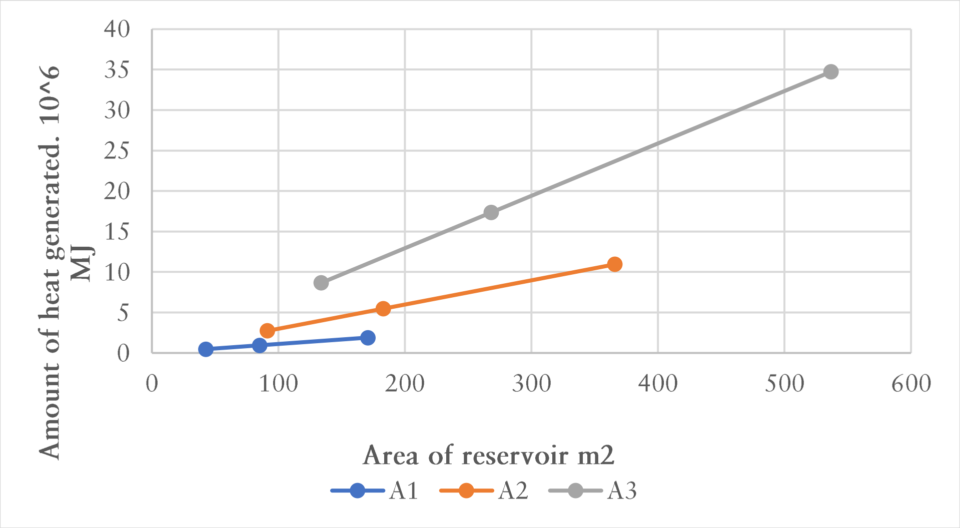

Figure 4. Area respect to the total amount of heat in the reservoir.

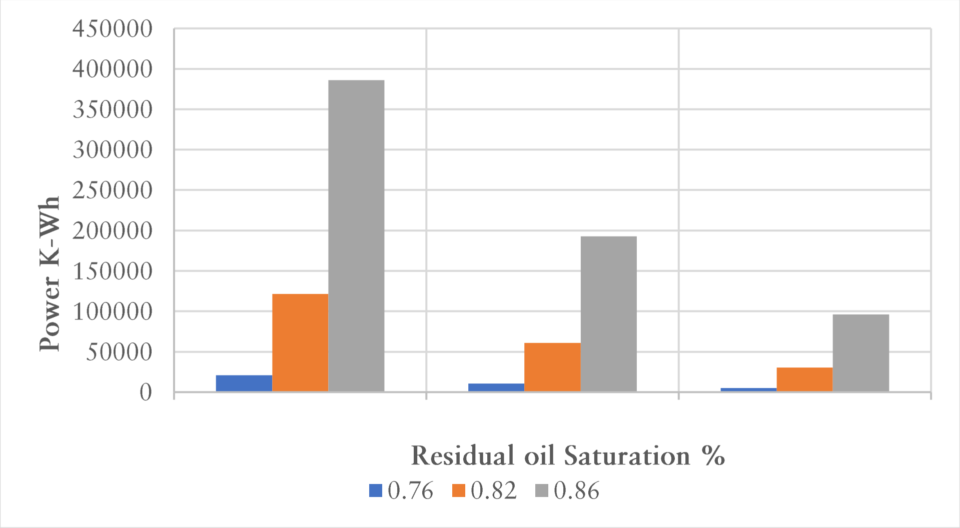

Figure 5. Power output to the residual oil saturation.

As seen in the graph in Figure 5, the higher the residual oil saturation, the higher will be the outcome of the power. However, it is to be noted that the highest residual oil saturation is not economically feasible. Nor it is practical to be utilized by the residual oil binary power plant. Because of the vast amount of heat generated, the reservoir will be extremely difficult to monitor and control. It can also lead to extensive formation damage, which could block the pathway to the residual oil.

As the residual oil saturation in this particular study is relatively high, it produces a higher amount of thermal energy. However, the most common percentage of residual oil saturation is around 60 % for the initial stage, which then reduces to around 30 per cent after preliminary EOR applications. In-situ combustion is a later stage EOR process and is applied to a smaller fraction of oil.

The pressure drops across three different flow rates of 0.01 m^3, 0.02 m^3, 0.03 m^3, and 0.04 m^3 are also estimated, categorized in Figure 6 below.

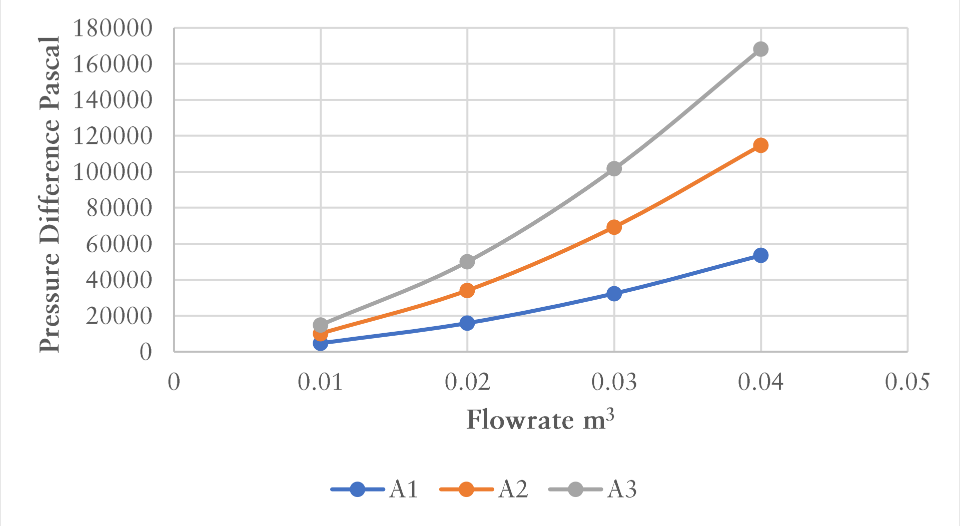

Figure 6. Pressure losses at different reservoir blocks.

Table 3. Pressure (Pascal) drop characterization.

Reservoir	At 0.01 m^3	At 0.02 m^3	At 0.03 m^3	At 0.04 m^3
A_1	53528.78485	32355.23776	15914.20295	4731.320845
A_2	114704.539	69332.65235	34101.86347	10138.54467
A_3	168233.3238	101687.8901	50016.06642	14869.86551

As seen in Table 3, by calculations, the lowest pressure drops occur at 0.04 m^3 and the highest at 0.01 m^3 across the four reservoir blocks. However, it should be noted that low-pressure drops are not entirely feasible for our proposed study. The ideal pressure drops are those occurring at 0.03 m^3 that is not too high for our system and are not too low for our system.

The results show that this particular well would produce extreme amounts of heat if combusted due to its high residual oil saturation. It would not be feasible for the small binary power plant used for this study. Such a high amount of heat would most likely damage the equipment. Therefore, proper methods and processes need to be developed so that the vast heat can be converted into power. The binary plant needs to be upgraded to work with the extreme conditions that this well presents.

CONCLUSION

A basic and straightforward theoretical estimation describing the retrofitting of an abandoned oil well into thermal energy production well using in-situ combustion EOR technique is proposed. This model combines the in-situ combustion technique with a heat exchanger. The applicability of the proposal is tested via a set of equations generating results at ideal conditions. Based on these simple equations, the amount of thermal energy generated is calculated. It is found that due to large amounts of residual oil saturation, 75-80%, the thermal energy generated is relatively high across the three reservoir zones. Due to this, the equipment's needed would have to be specifically designed for these conditions, which will ultimately add to the project's expenses. While the idea of utilizing an abandoned well for thermal energy is quite attractive for solving Pakistan's energy needs, it would need to go under extensive development before projects are commercially feasible.

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APPENDIX

Conversion from SI unit to the Metric system

Elements	SI System	Metric System
Temperature	°C (°C x 1.8) + 32	°F
Weight	Kg x 2.205	lb.
Density	Kg/m^3 x 16.018	lb. / ft^3
Length	m x 3.281	ft
Volume	m^3 x 6.29	bbl
Pressure	Pascal / 6895	psi
Viscosity	Pascal.sec x 10	poise
Power	Watt / 746	hp

Nomenclature

Elements	Symbol	Unit	Dimension
Viscosity of water	μ	Pascal.sec	m/Lt
Specific heat capacity of water	C_p	J/Kg/K	L^2/t^2T^1
Diameter of pipe	D	m	m
Darcy friction factor	f_D		
Length of pipe	L	m	m
Efficiency of Rankine Plant	η	%	
Power generated	P	KWatt	mL^2/t
Net power	P_{net}	KWatt	mL^2/t
Pump power rating	P_{pump}	KWatt	mL^2/t
Volumetric flow rate	Q	m^3/sec	m^3/t
Reynold's number	R_e		
Thermal power output	T_H	KWatt	mL^2/t
Velocity of fluid	v	m/sec	L/t
Pressure losses	ΔP	Pascal	m/Lt^2
Temperature difference	ΔT	°C	T

Density of water	ρ	Kg/m^3	m/L^3
Permeability	k	mDarcy	L^2
Water Saturation	Sw	%	--
Effective porosity	eff%	%	--