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Design and Analysis of Electric Power Production Unit for Low Enthalpy Geothermal Reservoir Applications

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Abstract**—**The subject of this paper is the design analysis of a single well power production unit from low enthalpy geothermal resources. A complexity of the project is defined by a low temperature heat source that usually makes such projects economically disadvantageous using the conventional binary power plant approach. A proposed new compact design is numerically analyzed. This paper describes a thermodynamic analysis, a working fluid choice, downhole heat exchanger (DHE) and turbine calculation results. The unit is able to produce 321 kW of electric power from a low enthalpy underground heat source utilizing n-Pentane as a working fluid. A geo-pressured reservoir located in Vermilion Parish, Louisiana, USA is selected as a prototype for the field application. With a brine temperature of 126℃, the optimal length of DHE is determined as 304.8 m (1000ft). All units (pipes, turbine, and pumps) are chosen from commercially available parts to bring this project closer to the industry requirements. Numerical calculations are based on petroleum industry standards. The project is sponsored by the Department of Energy of the US.

Keywords**—**Downhole Heat Exchangers, Geothermal Power Generation, Organic Rankine Cycle, Refrigerants, Working Fluids.

I. INTRODUCTION

GEOTHERMAL energy production has a lot of advantages comparing with fossil fuel plants, such as low emission of CO_2, low cost of produced electric power, and year-round availability. High and low enthalpy underground heat resources [1] are recognized in literature, where the last category is more abundant on earth, however, it is not economically attractive. The reservoir development requires expensive drilling operations, a large surface facility for a geo-fluid clean-up from dissolved components, and a binary cycle installation. Pumping brine from the depth to the surface is accompanied by fluid enthalpy losses and parasitic energy losses in the system. Therefore, overall power plant efficiency does not exceed 10-17% [8]. Consequently, low enthalpy reservoirs cannot compete with alternative energy production methods. This paper is an attempt to design a compact power unit inside of a single well utilizing binary ORC for electricity generation for a local usage. The design will consist of commercially available parts to bring the project closer to petroleum industry requirements as much as possible.

Downhole heat exchangers are appealing devices to complete the task. In the heat pump applications, DHEs interact with the formation through a pure conduction process. However, using formation fluid such as heat transport liquid is more advantageous [3], [4]. One may administrate brine flow using a conventional electric submersible pump. On the other side, flow control over the working fluid loop can be accomplished by a separate pump. Managing both fluid loops is a valuable method to extract a maximum possible heat from the reservoir.

There is a diversity of heat exchangers mentioned in a literature. Sliwa [5] classified them mainly in two configurations; co-axial, U-tube, and their implementations. The operating principle, however, is the same in both cases: fluid phase change to gas due to heating from a hot formation and condensation back to the liquid at the condenser. Steam is the best substance to implement in the energy extraction in the turbine and a liquid is convenient to transport heat from the reservoir. In this arrangement, a working fluid should satisfy to the several criteria depending on a system application.

Ideal working fluid features are widely discussed in the literature. In general, researchers mentioned an environmental safety, a low toxicity, a low boiling point with high thermal conductivity, a high critical point, a low melting point, and no corrosiveness [2], [3], [5]. Obviously, no real fluid can satisfy to all this requests. Taking into account the Kyoto protocol restrictions, the ozone depleting potential (ODP) classification and the global warming potential (GWP) requirements, the number of potential candidates diminishes to a few [6]. Water is a natural refrigerant [7]; however, the utilization of organic fluids instead of water has several advantages. Such that usage of small size turbines with fewer stages, a compact and, hence, less expensive air-cooling system, a possibility to run a cycle at temperatures below of a water freezing point. Therefore, all commercially available liquids applied in the heat and conditioning industry are becoming more and more popular for small heat harvesting applications. All refrigerants are classified into several categories of a flammability and toxicity according to ASHRAE standard 34. It is noteworthy to say that the most suitable for this project, refrigerants belong to high flammable and high toxic categories. All of them can be subdivided into dry and wet types [8]. Dry type fluids have a high vapor quality after the turbine stage. It increases turbine's efficiency and utilizes a maximum power at low revolutions. According to several researchers, Karla [6], Saleh [9], Schuster [10], Hettiarachchi [11], Iso-Pentane, R123, and n-Butane are the winner fluids for the low enthalpy EGS applications. These results are based on the following

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observations. Better performances have fluids with a high molecular weight, a high thermal conductivity, and high heat transfer coefficients. Fluids with low critical temperatures are more preferable. Summing up, a choice of the working fluid depends on the individual project parameters: a scheme configuration, temperature and pressure variations, an application, etc. Therefore, there is no a clear-cut winner in the refrigerant selection; hence, only the cycle optimization can clarify the right selection.

From the thermodynamic point of view, three main geothermal energy conversion types are mentioned in a literature: a trilateral, a subcritical, and a supercritical ORC. First and second types are out of consideration due to the high binary fluid flow rate requirements. Karla [6] stated that a fluid compressed and heated to a higher than a critical point gives more efficiency of the system than the subcritical cycle for the same refrigerant. At the same time, the efficiency of the cycle is a ratio of a turbine work to the total heat extracted from the reservoir [8]. This value depends on a working fluid type, a turbine and a pump choice, a DHE design, and hot and cold temperatures. To qualitatively evaluate the efficiency, one may consider an exergy destruction occurring in the system. Kanoglu [12] evaluated an existing geothermal power plant using exergy analysis. He obtained 35.2 % energy losses coming from the brine reinjection operation. To reduce losses a zero mass extraction principle can improve sustainability of the project.

A cooling process in the conventional geothermal power plant traditionally happens at the cooling towers or cooling pond, both require huge surface area. However, for a small scale heat extraction a simple air conditioner cooling unit can be utilized. The drawback of the commercially available chillers is a long length of a small diameter pipe (OD 1/2”) that would cause a high pressure drop and require an additional compressor installation. From the other side, the heat extracted from the system can be used at the surface facility, for example, as a hot water source.

There are several types of turbines used in the ORC industry. For this project only small expanders with high efficiency are considered. Possible installation inside of the wellbore is preferred. For this reason, screw expanders and water steam turbines are out of range. A primary attention falls into micro-turbines segment, which can have axial and radial configurations. Mikielewicz et al. [13] performed a design analysis of several constructional types of small turbines working on a low boiling temperature media. The most advantageous turbine has several stage axial design. Church (1956) developed an axial turbine calculation method based on the inlet and outlet velocity triangles analysis.

In a petroleum industry a pump assembly includes into itself an electric motor, a multistage pump, safety valves, aa tubing and may have a total length of 22 m (72 ft) [21]. Long assembly might be damaged during installation into a horizontal offset from a vertical well. Therefore, a buildup radius from the vertical pipe to the horizontal offset cannot exceed 20 degrees per 30.5 m (100ft) for the 7 inch diameter casing string. Centralizers along the pump assembly can support the equipment and provide a central pipe orientation [14]. Choice of a pump selection is strongly tied with the hydraulic head required to drive the liquid.

Earlier, Feng [15] proposed a geothermal unit design that theoretically produces 225 kW of energy using a binary organic Rankine cycle operating on the n-Butane fluid. A coaxial DHE was assumed to be installed in the horizontal offset of a vertical well drilled in geo-pressured reservoir. The rest of the ORC sections were expected to run at a surface facility. The numerical analysis with examination of a dipping angle and a length of the horizontal offset proved sustainability of the project for a long term operation.

A new approach of a heat extraction from the reservoir seems possible by utilizing the down-hole heat exchanger (DHE) at the reservoir depth. One of the big advantages is a compact design that requires only a single well and has a zero mass extraction of a geo-fluid to the surface [15]. This schematic can reduce seismic activity at the reservoir location region comparing with traditional way, and significantly reduce the area of a surface facility, and installation costs. The binary ORC can be mounted inside of the well due to a compact size of the turbine-generator assembly. In addition, a high safety operation without constantly attended personnel control is usually performed in the small ORC power plants [16]. This paper is an attempt to combine a new single-well technology with traditional organic Rankine cycle to increase a commercial interest to the geo-pressured reservoir development.

II. PROJECT DESCRIPTION

A. Geo-Pressured Reservoir Application

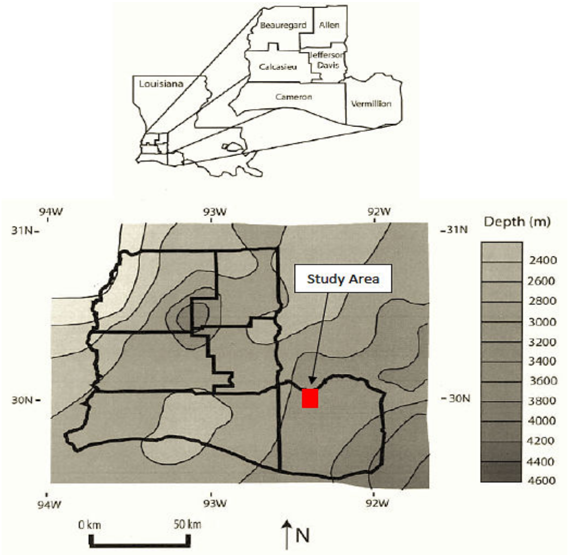

Fig. 1 Reservoir location [20]

Camerina A sand is a geo-pressured reservoir located near a Gueydan salt dome in the Vermillion Parish Louisiana, USA. A vertical depth varies between 4253 and 4479 meters. The geo-pressured layer creates higher geothermal gradients: 23.04

°C/km from the surface to the top of the geo-pressured zone (3,827 m); and 28.9°C/km in the pressured zone [20]. The formation sand is already saturated with the brine, so, there is no need to pump water into formation. According to the MIT report [1], this reservoir was named as the most geologically feasible sedimentary sand deposition in case of a future energy production.

B. Unit Design and Wellbore Geometry Determination

The proposed design of the DHE is a closed system device installed into the horizontal offset of a vertically drilled well. Basically, it is a coaxial pipe scheme where the hot geo-fluid enters into the outer annulus through the holes perforated to the porous reservoir rock. An electric submersible pump forces the geo-fluid from the porous rock through the production pipe to the injection side and back to the reservoir. The DHE length depends on working fluid and geo-fluid flow rates. It should be long enough to prevent drifting back of discharged “cold” brine into the inlet area [15].

A working fluid subsystem has a conventional electric pump installed in the condenser part at the surface facility. The pump directs refrigerant down toward the tubing of the DHE. Heat transfers through the DHE pipe wall from a hot brine to a cold binary fluid. The working fluid increases temperature but remains in a liquid form due to high hydrostatic pressure. While moving toward the surface, a working fluid drops pressure below saturation point and starts boiling. Eventually, two-phase flow transforms to a gas flow closer to the surface. The produced steam rotates turbine blades where the mechanical energy passes to the generator and converts to electricity. The discharged from the turbine vapor cools down and condensates at the surface chiller. The working fluid pump completes binary cycle forcing a cooled fluid downward back to the reservoir. A natural circulation may occur in the system due to the density change. However, to obtain the maximum power, the flow rate enhancement is necessary for both: geo-fluid and binary fluid loops [17].

III. COMPONENT DESIGN ASPECTS

A. Casing Design

A classical ORC thermodynamic analysis assumes negligible friction and gravitational pressure losses in the system. However, if the system is installed vertically inside of the deep well, they cannot be ignored. To complete the task, a geometric data of the well at each stage is required. Petroleum industry standards use several stages of pipes (casings) cemented into the formation with decreasing the pipe diameters toward the depth. Therefore, it is important at first to specify casing grades for obtaining necessary geometry data needed for system losses determination. The casing design was performed applying petroleum industry standards [18] based on formation pressure gradients of the reservoir location [20]. The analysis examined all loads (tension, compression, burst, collapse, buckling) acting on the casing and production strings. The selection choice is illustrated in the Fig. 2.

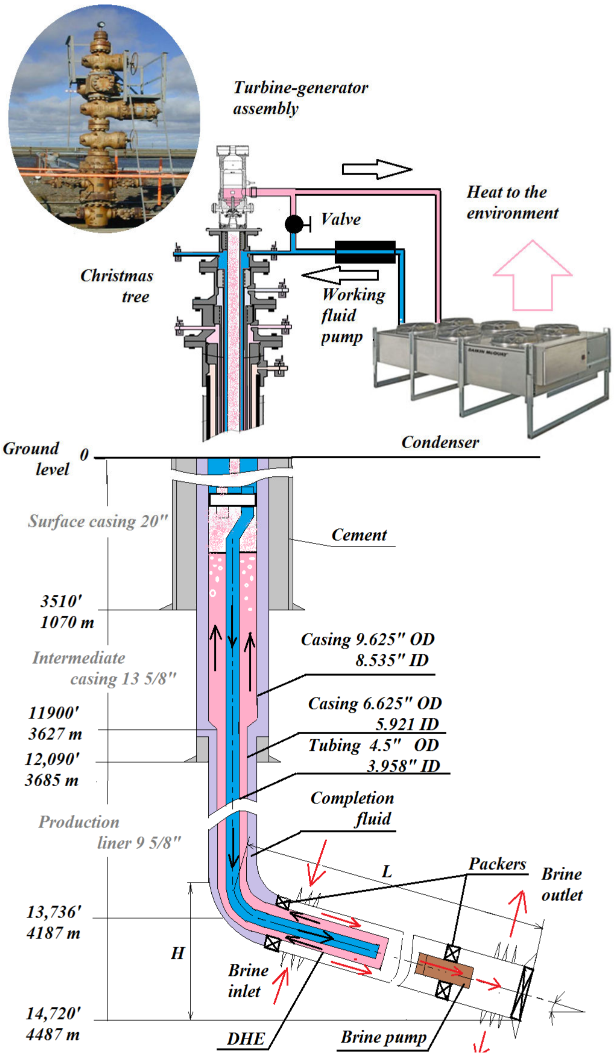

Fig. 2 Single well power unit schematic design

B. Turbine Calculations

Two design configurations of a turbine location are possible: on top of the Christmas tree and inside of the well. The first arrangement has some advantages. It is easy to complete the maintenance work if the turbine needs to be replaced. However, the second scheme makes the design more compact; however, a cooling process might be very complicated. In this project only the first case is considered.

C. DHE Analysis

In this project two main loops are used to complete the energy conversion: the reservoir fluid circulation loop and the secondary working fluid flow loop. These two systems attached to each other through the heat transfer process in the DHE. The working fluid flow in heat exchanger was considered in two configurations: a parallel and a counter flow. The mathematical solution is well defined by Feng [15].

D. Brine Pump Choice

Several pump types were considered, but the most preferable is an electric submersible pump. In this project, a pump needed to intake the brine into DHE and pushes it back to the reservoir at the end of the horizontal offset. Therefore, less power is obligatory comparing with the case when the fluid is driven up to the surface. A pump performance equation can be obtained from the separate analysis of both: production and injection sides. Note that the reservoir pressure remains constant in both cases with zero inclination angles.

$$P_{pump\,(in)} = P_{res} - \Delta P_{res} - \Delta P_{perf} - \Delta P_{gravel} - P_{\underset{well}{prod.}} \tag{1}$$

$$P_{\underset{(out)}{pump}} = P_{res} + g\left(D_{prod} - D_{inj}\right) - \Delta P_{res} - \Delta P_{perf} - \Delta P_{inj.well} \tag{2}$$

Then the total pump pressure P_{pump} is:

$$P_{pump} = P_{pump(out)} - P_{pump(in)} \tag{3}$$

where $P_{pump(in)}$, $P_{pump(out)}$ are inlet and outlet pressure of the pump; P_{res} is the reservoir pressure; ΔP_{res}, ΔP_{perf}, ΔP_{gravel} are the reservoir, perforations and the gravel pack pressure drops; $\Delta P_{prod.well}$, $\Delta P_{inj.well}$ are pressure drops in the production and injection sides; g_{geoth} is a pressure gradient; D_{prod} , D_{inj} are depths of the production and injection sides of the well. To simplify the case, let us assume that the reservoir and perforation-gravel pack pressure drops are equal in the production and injection sides of the well. Then, for the horizontally oriented well:

$$P_{pump} = \Delta P_{prod.well} + \Delta P_{inj.well} = \frac{\dot{m}^2}{2\rho}\left(\frac{f_{prod}L_{prod}}{A^2{}_{prod}D_{prod}} + \frac{f_{inj}L_{inj}}{A^2{}_{inj}D_{inj}}\right) \tag{4}$$

where f_{prod}, f_{inj}; L_{prod}, L_{inj} ; D_{prod}, D_{inj}; A_{prod}, A_{inj} are friction coefficients, lengths, pipe diameters and cross sectional areas of the production and injection sides. Note, that the production side represents a coaxial pipe with DHE installed, therefore:

$$D_{prod} = D_{a2o} - D_{a2i} \tag{5}$$

$$A_{prod} = A_{an2} = \pi\frac{D_{a2o}^2 - D_{a2i}^2}{4} \tag{6}$$

$$A_{inj} = \pi\frac{D_{inj}^2}{4} \tag{7}$$

The friction factor depends on a pipe roughness and flow regimes. In this analysis the roughness of 0.0006 m was assumed. Then the friction factor was calculated using a Colebrook relationship [18]. Consider a fully developed turbulent flow in both sections with the brine flow rate of 5.25 kg/sec.

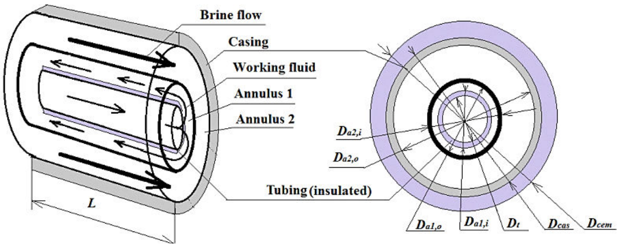

Fig. 3 The description scheme of DHE. While the brine enters and leaves the outer shale (annulus 2) in one direction, a working fluid travels through the tubing and changes its direction leaving the DHE as a hot fluid through the annulus 1

E. Surface Facility

The working fluid cooling process is assumed to run at the surface facility with an industry available air conditioner cooling device. The total heat removal from the system is the difference between a heat energy gained from the reservoir and a produced turbine work:

$$HEAT = E_{\underset{reservoir}{from}} - W_{turbine} \tag{8}$$

F. Thermodynamic Analysis and Fluid Selection Choice

Nodal analysis was implemented into the traditional power plant calculations. The method breaks a working fluid travel path into the several sections with control nodes at the end of the each interval. Several assumptions were considered to simplify the analysis:

- Constant fluid properties at each interval;
- No heat transfer between the well and a formation rock;
- Working fluid pipes have perfect insulation;
- Surface air and geo-fluid temperatures are 30°C, and 126 °C respectively;
- Steady-state conditions.

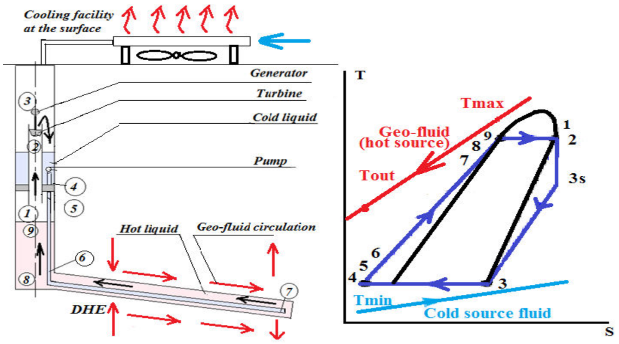

Fig. 4 The thermodynamic analysis stages (left), a general T-S diagram for the system with the DHE (right). Stage description: 1-vapor/liquid boundary, 2-turbine inlet, 3,3'- turbine outlet, 4,4'-condenser inlet and outlet, 5-pump outlet, 6-end of vertical interval, 7-end of insulated tubing (cold), 8-retern back to the vertical pipe (hot), 9-liquid/vapor boundary

For the each stage the thermodynamic parameters were corrected with respect to the friction and gravity pressure drops [18]:

$$\Delta P = P_{fric} + P_{gravity} = \frac{f\Delta L\rho V^2}{2D_h} + \rho g\Delta L sin(\alpha) \tag{9}$$

For the DHE calculations only a horizontal orientation was considered $\alpha = 0°$, and for the vertical sections $\alpha = 90°$.

As it is seen from the T-S diagram in Fig. 5, the shaded area represents reservoir brine and surface temperature boundaries of the system. The maximum area of a useful work belongs to n-Pentane which is a dry-type liquid [5]. In contrast, R-134a belongs to the “wet” refrigerant, where after the turbine stage there is a liquid fraction. Therefore, due to specifics of the design R-134a is not a good choice. Exergy destruction is calculated from [12]:

$$e = h - h_0 - T_0(s - s_0) \tag{10}$$

where h, S, T are the enthalpy, the entropy, and the temperature. A dead stage values with zero asterisk are bolded in Table I.

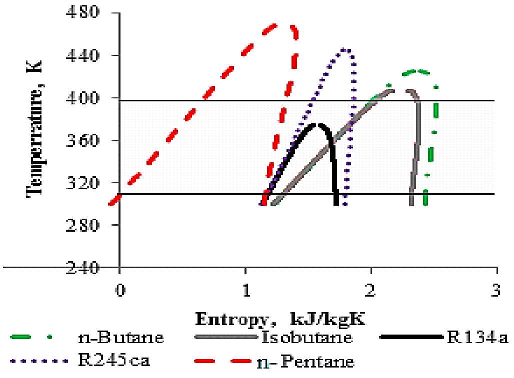

Fig. 5 T-S diagram of the working fluids. The useful work is equal to the shaded zone between cold and hot temperatures of the cycle

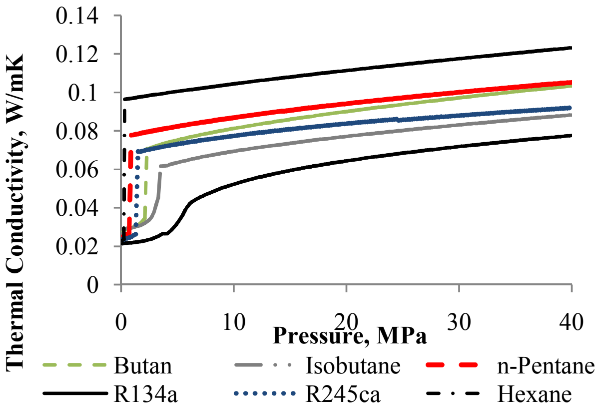

Fig. 6 The working fluid thermal conductivity change with pressure grows at a constant temperature. The thermal conductivity increases about five times with pressurizing the refrigerant up to 40 MPa

IV. RESULTS

Several refrigerants were compared in the thermodynamic analysis: n-Butane, Isobutane, R-134a, R245ca, and n-Pentane. Fluid properties for the each state were calculated using online software of the National Institute of Standards and Technology.

The system analysis was performed the using Matlab Simulink software. The data verification with Feng [15] is shown in Appendix. Figs. 7 and 8 illustrate results of the temperature development with respect to DHE length. Brine and working fluid flow rates were assumed to be 5.25 kg/sec and 4.53 kg/sec respectively [16]. N-Pentane was considered as the working fluid in two configurations of DHE: parallel and counter flow. In the first scheme the temperature reached up to 118.7℃ with 304 meter of an exchanger length, comparing with 87℃ in a parallel flow simulation. Therefore, the counter flow configuration was considered for further analysis.

The results of the thermodynamic analysis with n-Pentane are presented in Table I. The maximum pressure at the DHE is close to 28 MPa with the reservoir pressure of 80 MPa. If the DHE pipe erodes there would not be any leakage to the formation. The brine from the reservoir would displace the working fluid and rise its level toward the surface. Eventually, at the some depth the pressure equilibrium would be reached and the organic fluid would be trapped inside of the well. In an emergency well shut down case, the system needs an automatic control valve, which is a common practice in the petroleum industry.

The energy loss in the cooler was calculated using the example of a real device available in industry. According to the Witt’s company data and their described procedure for selection [19], the best suitable air-cooler is chosen WCE 147-10 with the seven units of total 72 chillers. An electricity consumption of all electric motors rotating fans was calculated to be 32.83 kW. Additionally, a 2 kW electric motor is needed for the gas compressor to overcome frictional losses in 0.019 m (¾ inch) diameter pipes. Submersible pumps are used in the project for brine and working fluid circulations.

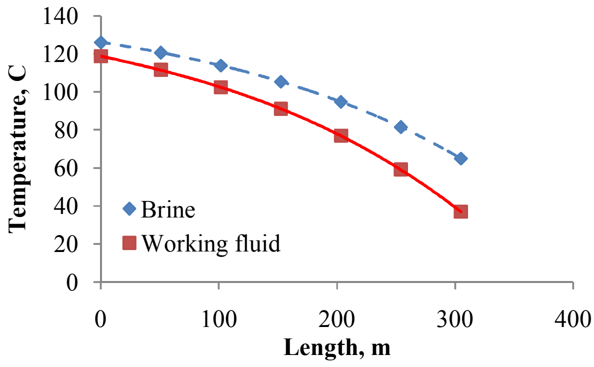

Fig. 7 Counter flow DHE temperature distribution along the well with reservoir heat included. Reservoir heat penetrates not only by geo-fluid, but through the pipe wall cemented in the rock. This explains the concaved upward shapes of the curves

According to the design, there is no need in lengthy pump assemblies, which contain several stages to provide a high pressure head to push the brine to the surface. Therefore, both pumps (the working fluid and the brine) have only one stage. It is enough to control the circulation with a total consumed energy of 2 kW. The brine pump pressure requirement was calculated with (4). The total friction pressure loss in the both production and injection sides is 949 Pa with data from Table A. Based on that, the most suitable pump is chosen from the Weatherford company brochure.

Table II illustrates a comparison of working fluids in terms of their power generation ability under the determined conditions. The winner fluid is n-Pentane. A toluene was included into the calculation for a comparison purposes. Due to the high toxicity and flammability it cannot be used in this project; however, it deserves some attention from the thermodynamic point of view.

The turbine analysis was performed by calculating the inlet and outlet impulse velocity triangles and the single blade work from [16]. For the comparison purposes, three fluids were used: n-Pentane, Toluene, and R-245ca. The results are in Table III.

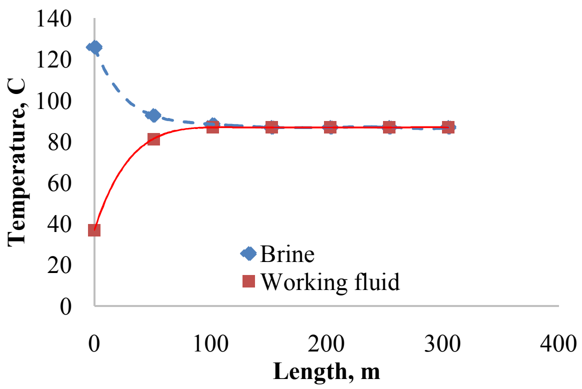

Fig. 8 Parallel flow calculations without reservoir heat in consideration and assuming no heat transfer to the tubing

TABLE I
THERMODYNAMIC CALCULATION RESULTS WITH N-PENTANE AS A WORKING FLUID

Depth m	Stage	Pressure, Pa	Temp K	Enthalpy kJ/kg	Entropy kJ/kg K	Exergy
0	**0**	**101,325**	**293**	**130.37**	**0.496**	**0**
-10	Gas 1	1,018,300	399	499.49	1.323	575
-5	Gas 2	1,010,212	398.6	498.90	1.323	572
+3	Gas3s	104,070	339.5	411.65	1.329	196
+3	Gas 3	104,070	346	424.25	1.357	188
0	Gas 4	104,070	315	359.38	1.170	143
0	Liq 4'	104,070	310	1.86	0.006	68
0	Liq. 5	105,070	310	72.15	0.224	98
-4480	Liq. 6	27,863,585	310	194.00	0.564	198
-4480	Liq. 7	27,434,947	310	194.00	0.565	200
-4480	Liq. 8	23,945,533	399	411.98	1.196	346
-2680	Liq 8'	11,196,704	399	404.87	1.237	260
-10	Liq. 9	1,018,300	399	404.67	1.285	195

TABLE II
A COMPARISON OF THE WORKING FLUID CANDIDATES

Parameters	R134a	R245ca	Iso-Butane	Toluene	n-Pentane
Heat from reservoir (kW)	1070.67	1239.72	1908.57	2505.80	2397.56
Thermal efficiency (%)	12.56	14.56	14.75	16.23	14.85
Turbine work (kW)	134.47	181.46	281.68	406.63	356.06
Electric power (kW)	99.64	146.63	246.85	371.80	321.23

The turbine was assumed as a multistage coaxial device with equal blades of diameters 0.152 m (6 inch). The assumed steam pipe inlet diameter is 0.102 m (4 inch) and the nozzle angle is 12 degrees. An additional reducing gear box with 97% efficiency is installed to decrease revolutions between the turbine and the generator.

TABLE III
THE TURBINE CALCULATION RESULTS WITH THE DIFFERENT FLUIDS

Fluid	Turbine efficiency	Shaft rev/min	Stages	Mass flow rate, kg/sec / lbm/sec
n-Pentane	0.801	10,227	5	4.53 / 9.93
Toluene	0.800	11,037	5	5.05 / 11.13
R-245ca	0.803	11,675	2	4.45 / 9.81

APPENDIX

A. Data Used in Analysis

TABLE A
INPUT DATA FOR THE ANALYSIS

DHE size, m		
Casing 1	Diameter inner	0.1536
	Diameter outer	0.1936
Casing 2	Diameter inner	0.2190
	Diameter outer	0.2445
Cement sheath	Diameter outer	0.3105
Tubing	Diameter inner	0.1143
	Diameter outer	0.1000
Thermal conductivity, W/mK		
Pipe		45.0
Cement		0.580
Formation Rock		1.900
Geo-fluid		0.519
n-Pentane		0.107
Viscosity, Pa sec		
n-Pentane		0.00017
Geo-fluid		0.00011
Specific heat, kJ/kg K		
n-Pentane		2.736
Geo-fluid		3.182
Density, kg/m^3		
n-Pentane		582
Geo-fluid		1000

B. Verification with Feng [6]

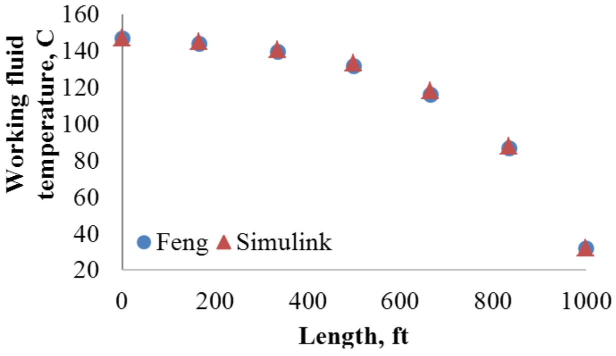

Fig. 9 The Simulink model verification with the data from Feng [15]

VI. CONCLUSIONS

- The binary ORC was successfully applied into the single well design with the DHE installed into the reservoir depth. A single well configuration with the turbine on top of the well was analyzed. This case has advantages in the service work and maintenance.
- The DHE with the counter flow scheme is the most efficient. The working fluid temperature can reach up to 118.7℃ comparing with 87℃ in the parallel flow configuration. The DHE length is 304.8 m (1000 ft).
- N-Pentane is the most suitable working fluid that gives the maximum efficiency of 14.85% and the electric power of 321.23 kW from the single unit. This project is well competes with industry examples [16].
- The turbine design with the chosen fluid requires five stages in the coaxial configuration. The turbine shaft has maximum 10,227 rev/min. A reduction gearbox is required to connect with generator. The calculated turbine efficiency is 80%. The corrected n-Pentane mass flow rate is 4.53 kg/sec.
- The cooling of the system is illustrated in the example of a commercially available device. The process involves 72 cooling blocks WCE 147-10 (Witt company). The calculated pinch point temperature is 7℃.
- The unit is safe in case of an underground pollution. If the erosional DHE destruction occurs a high pressure geo-fluid would displace n-Pentane up toward the surface due to the pressure differences and trap it preventing from the underground pollution.

V.FUTURE RESEARCH

To make an objective evaluation of the chosen DHE configuration and the working fluid, it is necessary to simulate the reservoir response for a cooling process. A possible salt precipitation, erosion, and a sand production analysis can help to determine weak sides of the system and a maximum allowable geo-fluid flow rate. The DHE model with several inflow sections might increase the brine flow rate that would enhance the reservoir heat extraction efficiency.

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