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Novel Approach to Co-Produce Geothermal Energy from Oil and Gas Wells

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ABSTRACT

Co-production of thermal energy from producing oil and gas wells has been receiving interest and attention in recent times. For instance, existing assets at moderately high temperatures (~120°C to 150°C) can be worked over to enable extraction of some of the thermal energy in the produced fluids. The extracted thermal energy can be used either directly or to produce electricity, serving to reduce the carbon footprint of existing assets.

This work presents some novel ideas for recovery of thermal energy from producing oil and gas assets. A novel Annular Circulation Co-production (ACC) approach to thermal energy extraction, first published by the authors in 2011 (Suryanarayana, et al.), is revisited. In this method, a separate circulation loop within the production tubing by production casing annulus is used to circulate a working fluid. The working fluid extracts heat from the produced fluid in a way analogous to a flow heat exchanger. In this work, we describe a thermos-hydraulic model developed to calculate ACC system performance, and several performance metrics are defined to characterize system performance. The model is used to evaluate the effect of various sensitivity parameters, including circulation direction, divider string insulation, circulation depth, and working fluid flow rate. Finally, a high-level procedure to implement the workover is describe, facilitating modification of some existing oil and gas wells to produce attractive levels of thermal energy, either for direct use or for electricity generation.

1. INTRODUCTION

Arguably the earliest practical attempt at a co-produced system was the demonstration power plant on the Pleasant Bayou field, reported by Riney (1991), where existing wells were used to extract both gas and hot water and to produce electricity. An article by McKenna et al. (2005) even suggested that active prolific producers in the Gulf of Mexico might be viable candidates. The efficacy of co-produced systems depends on the availability of fields with high geothermal gradients. The study of Tester (2006) produced several maps of the US geothermal resource potential. Augustine and Falkenstern (2010) have presented a database of existing oil and gas wells and a method to assess their potential for thermal energy recovery.

The studies of Zhang et al. (2008) and Xin et al. (2012) document efforts in China's Huabei field. An excellent review of co-produced systems in the two decades since the Pleasant Bayou experiment is presented by Soldo and Alimonti (2015) who proposed a selection matrix to screen viable candidates in Italy's Villafortuna-Trecate oil field. The importance of a selection protocol is highlighted by the study of Gosnold et al. (2013) concluded that flow rates from shale producers in North Dakota's Williston Basin were too low to sustain a co-produced system. Tóth et al. (2018) investigated the feasibility of Hungary's abandoned oil and gas fields based on the high geothermal gradients in the region to provide a good source of direct heating from geothermal wells. A study by Suryanarayana et al. (2011) looked at many aspects of co-produced systems wherein several alternative systems were compared. In particular, the implications of wellbore design, pressure management, oil and gas delivery systems, and surface system flexibility to handle changing production parameters and fluid properties were examined.

Many studies of co-produced systems are hypothetical in nature such as those of Molina et al. (2021) and Patihk (2022) investigating the potential of co-produced systems in Abu Dhabi and Trinidad, respectively. Céspedes (2022) concluded that a carbon footprint reduction between 10% to 50% was possible in two of the Columbian fields of interest in their study. Exhaustive reviews of recent efforts and the path forward is presented by Santos et al. (2022) and Cano et al (2022).

2. ANNULAR CIRCULATION CO-PRODUCTION (ACC) CONCEPT

The authors have developed the novel Annular Ciculation Co-Production (ACC) concept (Suryanarayana et al. 2011), which may be applied to most mature hydrocarbon wells. Figure 1 shows the concept. The original hydrocarbon producer (left) is a vertical well. In this present case, the well has been producing hydrocarbon from a reservoir at 3048 m (10,000 ft) through a 5-1/2-inch, 17-lb/ft tubing. The production casing is 9-5/8-inch, 47-lb/ft. The present production is 10000 bbl/day with 95% watercut.

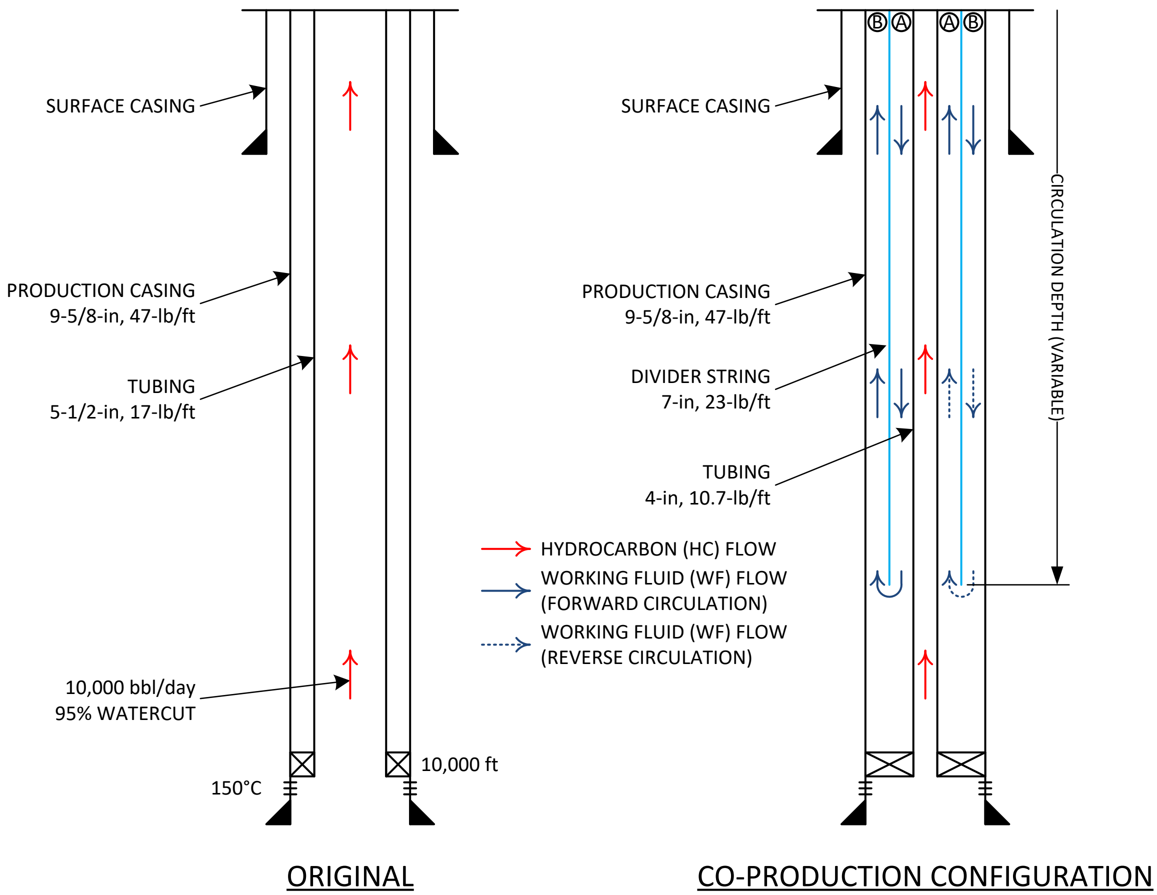

Figure 1: Original Well Configuration and Configuration of Well Converted to Co-Production.

With the ACC concept, the well is re-configured as follows (Figure 1, right). The tubing is replaced with a smaller 4-inch, 10.7-lb/ft tubing, and the hydrocarbon (HC) stream flows up inside this tubing. (A nodal analysis has indicated that the well has sufficient deliverability to maintain its current production rate with the smaller tubing.) A 7-inch, 23-lb/ft divider string has been installed in the annular space between the (now smaller) tubing and the (original) production casing. This divider string separates the region between the tubing and production casing into two annular paths, labeled A annulus and B annulus. The divider string need not extend the entire length of the well, and the effect of the variable circulation depth is examined later in this paper. A working fluid (WF) is circulated through these two annuli. The circulation may be in the forward direction (down A annulus and up B annulus) or in the reverse direction (down B annulus and up A annulus).

Compared to surface utilization of geothermal energy, the ACC offers two advantages: first, the produced HC stream may be corrosive, may contain hydrogen sulfide (H_2S) or may be at high pressure, so handling these in surface heat exchange equipment may be problematic. The ACC concept utilizes the equipment already in the well, especially the long length and large surface area of the tubing, to construct the heat exchanger. The tubing string would already been designed to contain the produced fluid, including its corrosive nature, H_2S and high pressure, so no additional considerations are needed. Second, the ACC concept intercepts and recovers the heat already being lost to formation, thereby improving thermal recovery.

2. THERMO-HYDRAULIC MODEL

The authors have developed a thermo-hydraulic model to study heat extraction using the ACC concept. The model is described using the control volumes, and mass and energy flows shown in Figure 2.

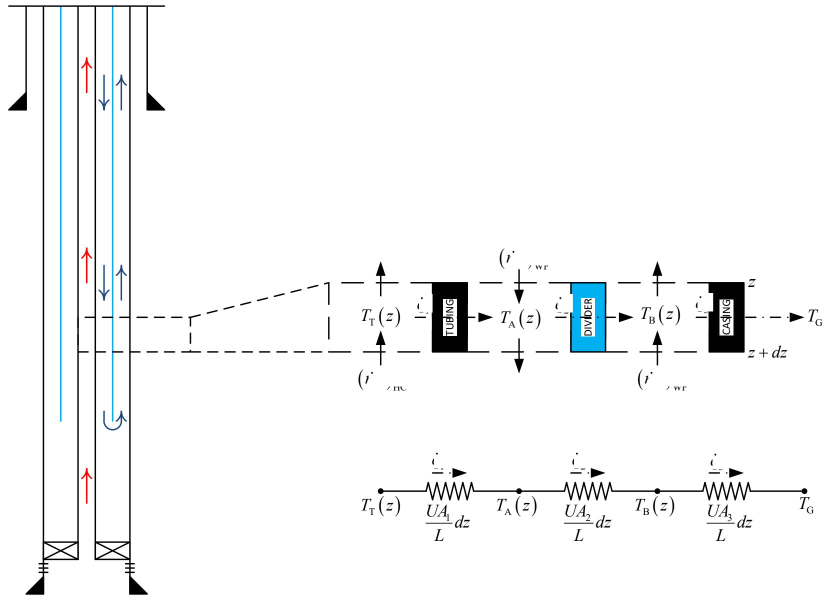

Figure 2: Energy Flows and Heat Transfer Network for Thermo-Hydraulic Model.

Our objective is to determine the three fluid temperature profiles $T_{\mathrm{T}}(z)$, $T_{\mathrm{A}}(z)$ and $T_{\mathrm{B}}(z)$. Using the formulation in Figure 2, three first-order differential equations may be developed for these three unknowns as follows:

$$(\dot{m}\;)_{\mathrm{HC}} \frac{dT}{dz} = \frac{UA_1}{L}\left(T_{\mathrm{T}} - T_{\mathrm{A}}\right) \tag{1}$$

$$-(\dot{m}\;)_{\mathrm{WF}} \frac{dT}{dz} = \frac{UA_1}{L}\left(T_{\mathrm{A}} - T_{\mathrm{T}}\right) + \frac{UA_2}{L}\left(T_{\mathrm{A}} - T_{\mathrm{B}}\right) \tag{2}$$

$$(\dot{m}\;)_{\mathrm{WF}} \frac{dT}{dz} = \frac{UA_2}{L}\left(T_{\mathrm{B}} - T_{\mathrm{A}}\right) + \frac{UA_3}{L}\left(T_{\mathrm{B}} - T_{\mathrm{G}}\right) \tag{3}$$

The three initial conditions required to solve the above equations are:

$$T_{\mathrm{F}}(L) = T_{\mathrm{HC,in}} \tag{4}$$

$$T_{\mathrm{A}}(0) = T_{\mathrm{WF,in}} \tag{5}$$

$$T_{\mathrm{A}}(L) = T_{\mathrm{B}}(L) \tag{6}$$

Although the above equations are written for the forward circulation direction (as shown), they may be converted to the reverse circulation direction by changing the signs of the left-hand terms in equations (2) and (3). Also, in the reverse circulation direction, the initial condition of equation (5) is replaced by:

$$T_{\mathrm{B}}(0) = T_{\mathrm{WF,in}} \tag{7}$$

The quantity of interest is $T_{\mathrm{WF,out}}$, which is $T_B(0)$ in the forward circulation direction and $T_A(0)$ in the reverse circulation direction.

The overall heat transfer conductances are given by the following equations:

$$UA_1 = \left[\frac{1}{h_{\mathrm{T}}\pi d_{\mathrm{t,i}}L} + \frac{\ln\left(d_{\mathrm{t,o}}/d_{\mathrm{t,i}}\right)}{2\pi k_{\mathrm{t}}L} + \frac{1}{h_{\mathrm{A}}\pi d_{\mathrm{t,o}}L}\right]^{-1} \tag{8}$$

$$UA_2 = \left[\frac{1}{h_{\mathrm{A}}\pi d_{\mathrm{d,i}}L} + \frac{\ln\left(d_{\mathrm{d,o}}/d_{\mathrm{d,i}}\right)}{2\pi k_{\mathrm{d}}L} + \frac{1}{h_{\mathrm{B}}\pi d_{\mathrm{d,o}}L}\right]^{-1} \tag{9}$$

$$UA_3 = \left[\frac{1}{h_{\mathrm{B}} \pi d_{\mathrm{c,i}} L} + \frac{\ln\left(d_{\mathrm{c,o}}/d_{\mathrm{c,i}}\right)}{2\pi k_{\mathrm{c}} L} + R_{\mathrm{f}}(\tau) \right]^{-1} \tag{10}$$

Heat transfer coefficients $h_{\mathrm{T}}, h_{\mathrm{A}}$ and h_{B} may be calculated using appropriate correlations such as Dittus-Boelter (1930). $R_{\mathrm{f}}(\tau)$ is a time-dependent formation heat transfer resistance and may be calculated using the approach described in Ramey (1962).

For the hydraulic component of the model, the pressure drops are calculated using the following equation:

$$P(L) - P(0) = \rho g L \pm \frac{1}{2} f \frac{L}{d_{\mathrm{H}}} \left(\frac{\dot{m}}{\bar{\rho} A_{\mathrm{F}}^2} \right) \tag{11}$$

For the last term of equation (12), positive sign is used for an up-flowing passage and negative sign is used for a down-flowing passage. Friction factor *f* is obtained from Moody (1944) chart or using the formulas given by White (1986, pp. 313–314).

Finally, the model must calculate the power required by the circulation pump, which is necessary to pump the working fluid through the well. For an incompressible fluid (e.g., water), the pump power is given by

$$\dot{W}_P = \frac{\dot{m}\,\Delta P}{\rho_{\mathrm{WF}}} = \frac{\dot{m}\,\left| P_{\mathrm{A}} - P_{\mathrm{B}} \right|}{\rho_{\mathrm{WF}}} \tag{12}$$

The above equations may be discretized and solved using an iterative technique. This approach has been implemented in a Microsoft Excel workbook. The model obtains necessary fluid properties using NIST REFPROP (Lemmon et al. 2018) package, so any suitable fluid (including fluid mixtures) available in the REFPROP package may be used as WF. (The present study uses only water as WF.)

2.1 Performance Metrics

This section develops the metrics necessary to evaluate the performance of the co-production system.

One possible metric is the fraction of available thermal energy that is recovered by the system. The available thermal energy is maximized when the hydrocarbon stream exits the wellbore at the WF inlet temperature, which is a specified, input parameter. Thus, fraction of thermal energy recovered is calculated by:

$$\phi = \frac{\dot{q}}{\dot{q}_{\mathrm{MAX}}} = \frac{\dot{m} c_{p,\mathrm{WF}} \left(T_{\mathrm{WF,out}} - T_{\mathrm{WF,in}}\right)}{\dot{m} c_{p,\mathrm{HC}} \left(T_{\mathrm{HC,in}} - T_{\mathrm{WF,in}}\right)} \tag{13}$$

The ACC system is essentially a heat pump, which uses mechanical power to extract thermal energy. The performance of a heat pump is measured by its coefficient of performance (cop) (Reynolds and Perkins 1977, p.142), defined as the ratio of the thermal energy recovered to the mechanical power used:

$$cop = \frac{\dot{q}}{\dot{W}_P} = \frac{\dot{m} c_{p,\mathrm{WF}} \left(T_{\mathrm{WF,out}} - T_{\mathrm{WF,in}}\right)}{\dot{W}_P} \tag{14}$$

If the recovered thermal energy is used for electricity production, thermal efficiency is another possible metric. However, thermal efficiency depends strongly on the configuration of the surface system used to produce electricity. Therefore, thermal efficiency is not used in the present study.

3. RESULTS AND DISCUSSION

In this section, the ACC system performance is evaluated with the following sensitivities:

- Circulation direction
- Divider string thermal conductivity (insulation)
- Circulation depth
- WF flow rate

This study uses water as WF, with the WF inlet temperature specified as 40°C.

3.1 Original Configuration

It is instructive to look at the behavior of the original HC producer to understand the maximum thermal energy available for recovery; the ACC system performance may then be compared to this maximum value.

The original HC well is producing 500 bbl/d of oil with 95% watercut from a reservoir at 3,048 ft and 150°C. This corresponds to an oil mass flow rate of 0.86 kg/s and water mass flow rate of 17.48 kg/s, for a total mass flow rate of 18.34 kg/s. The specific heat of the combined stream is 3.9 kJ/kg/°C. Flowing bottomhole pressure is 34.5 MPa.

Figure 3 shows the temperature profile of the hydrocarbon fluid as it flows up the tubing string. The hydrocarbon fluid arrives at the surface with a temperature of 123.0°C, thus losing 1930 kW of thermal energy to the formation. The pressure drop is 28.6 MPa, of which 28.1 MPa is due to gravity and 0.5 MPa is due to friction.

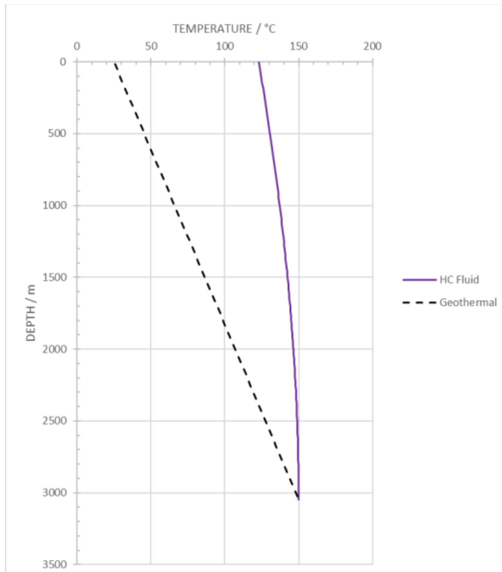

Figure 3: Temperature Profile of Hydrocarbon Stream in the Original Well.

The maximum thermal availability from the original well is then calculated assuming that the HC stream is cooled to the WF inlet temperature of 40°C:

$$\dot{Q}_{MAX} \quad 48\frac{\text{kg}}{\text{s}}\times 3.9\frac{\text{kJ}}{\text{kg}\cdot{}^{\circ}\text{C}}\times\left(150.0^{\circ}\text{C}-40.0^{\circ}\text{C}\right)=7500\text{ kW} \qquad (15)$$

Thus, heat loss to the formation in the original well represents 26% of the thermal availability of the hydrocarbon stream.

3.2 ACC Circulation Direction

WF may be circulated in either forward or reverse direction. In the forward direction, WF flows down the A annulus between the tubing and the divider string, and returns through the B annulus between the divider string and production casing. The WF flow direction in the A annulus is opposite that of the HC stream inside the tubing. This configuration represents a counterflow heat exchanger between the HC and WF streams.

In the reverse direction, WF flows down the B annulus between the divider string and production casing, and returns through the A annulus between the tubing and divider string. The WF flow direction in the A annulus is the same as the HC stream inside the tubing. This configuration represents a parallel flow heat exchanger between the HC and WF streams.

Table 4 summarizes the behavior of the two configurations.

Table 4: Results for Forward and Reverse WF Flow Directions

Circulation Direction	Circulation Depth	Divider	WF Flow Rate	WF Outlet Temperature	Thermal Recovery	Pump Power	ϕ	*cop*
Forward	3048 m	Steel	16.2 kg/s	85.8°C	3070 kW	19.4 kW	40.9%	158
Reverse	3048 m	Steel	16.2 kg/s	79.9°C	2670 kW	20.7 kW	35.6%	129

The temperature profiles for the two cases are shown in Figure 5. Blue lines indicate downward WF flow, and red lines indicate upward WF flow. The figure on the right focuses on the top 1000 m of the well, where almost all of the heat transfer occurs.

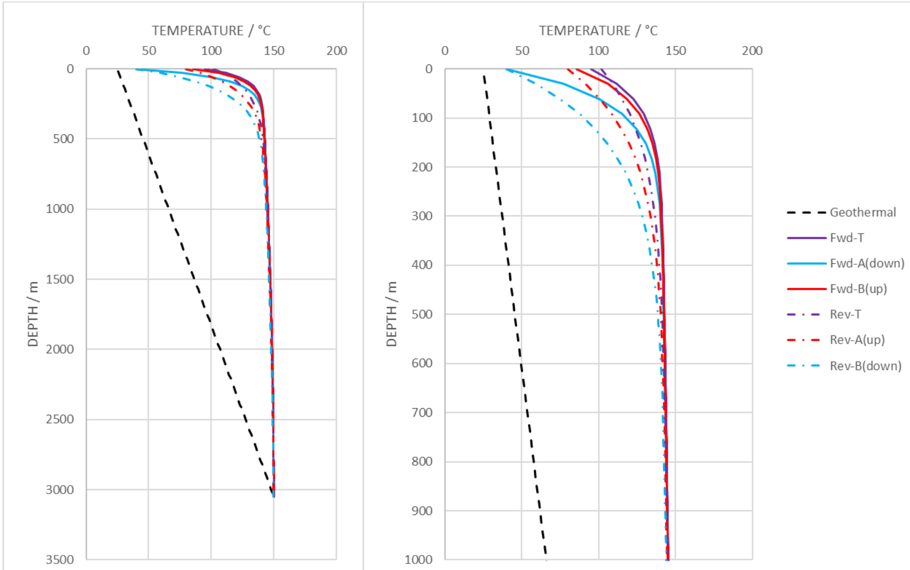

Figure 5: Temperature profiles for forward and reverse WF circulation directions.

Figure 6 plots the temperature difference between the HC stream the tubing (T_T) and WF stream in annulus A (T_A), again focusing on the top 1000 m of the well. The heat transfer of interest from HC to WF is driven by this temperature difference. Note that the temperature difference is, on average, higher for the forward configuration, as expected from a counterflow heat exchanger configuration. This is why forward circulation configuration exhibits better performance compared to the reverse circulation configuration.

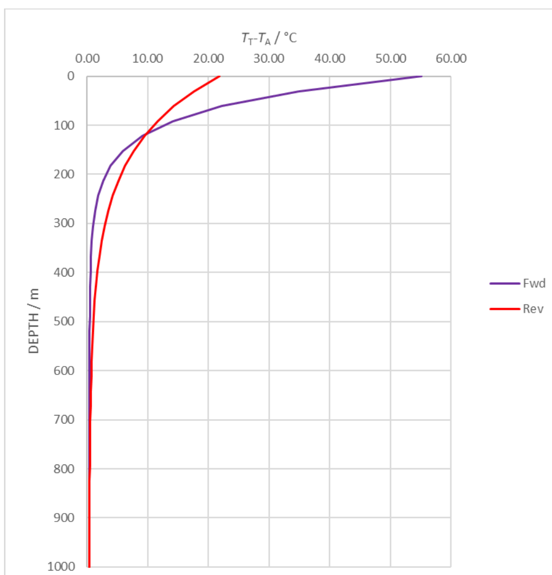

Figure 6: Temperature difference between HC and WF streams driving thermal heat recovery.

3.3 ACC Divider Insulation

In addition, the WF in A and B annuli, themselves, form a counterflow heat exchanger. Therefore, some of the heat transferred to WF in the A annulus may subsequently transferred to WF in the B annulus. This will reduce the temperature difference and therefore result in lower heat transfer. It is necessary to insulate the divider string to improve heat recovery.

Two methods for insulating the divider are examined. The first is manufacturing the divider string from a composite material, which has much lower thermal conductivity compared to steel (GWE pumpenboese GmbH 2019). This approach is feasible because the divider string is not subjected to any significant pressure differential. In fact, the only pressure differential that the divider string needs to resist is the frictional pressure drop, which is about 1 MPa (150 psi).

The second method is using vacuum insulated tubing (VIT) for the divider. Effective thermal conductivity of VIT is two orders of magnitude lower than that of composite material (Vallourec 2014). The primary disadvantage of the VIT approach is the reduction in flow area in A and/or B annuli. This is because VIT is manufactured from concentric tubulars. In this case, a 7-inch by 5-1/2-inch VIT is used. The other disadvantages are that VIT are more expensive and some hydrocarbon wells may not have the space for VIT installation.

The results are shown in Table 7, and the temperature profiles are shown in Figure 8.

Table 7: Results for Divider Insulation Options

Circulation Direction	Circulation Depth	Divider	WF Flow Rate	WF Outlet Temperature	Thermal Recovery	Pump Power	ϕ	*cop*
Forward	3048 m	Steel	16.2 kg/s	85.8°C	3070 kW	19.4 kW	40.9%	158
Forward	3048 m	Composite	16.2 kg/s	125.3°C	5730 kW	11.7 kW	76.4%	491
Forward	3048 m	VIT	16.2 kg/s	137.4°C	6560 kW	58.5 kW	87.5%	112

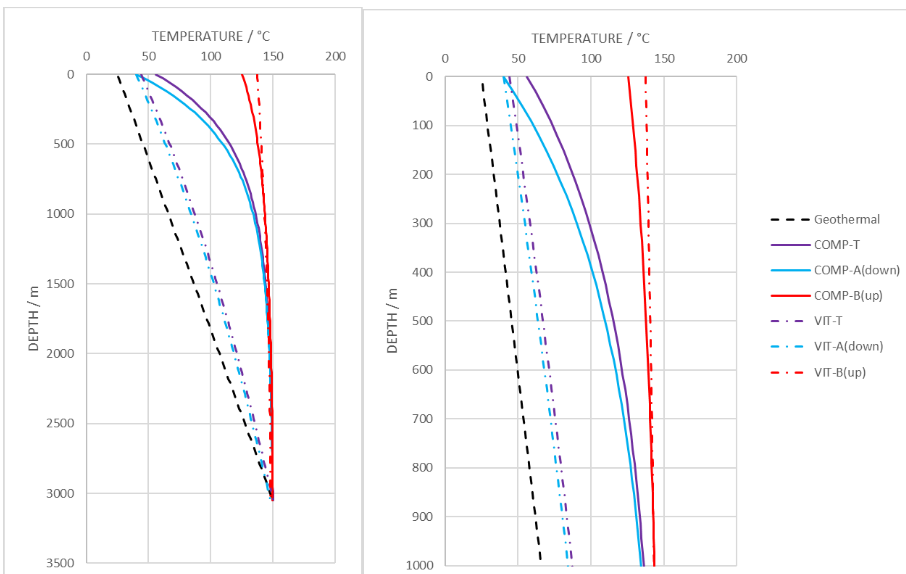

Figure 8: Temperature profiles for composite (solid) and VIT divider.

The composite divider option increases thermal recovery by a factor of almost two. Compared to the base (steel) case, the pump power requirement is slightly reduced; this is because of the thermosiphon effect resulting from the hotter column of WF returning to the surface in the B annulus. The VIT option increases the thermal recovery by another 15% but at the expense of significant increase in the pump power requirement.

3.4 Circulation Depth

Figures 5, 6 and 8 indicate that most of the heat transfer occurs in the top portion of the well. Therefore, it may not be necessary to use the entire well length for circulation. Reducing the circulation depth will decrease the pump power requirement and reduce the cost of the divider string.

In this section, the effect of reducing the circulation depth is evaluated. When the circulation depth is less than 3048 m, the HC inlet temperature must also be adjusted to account for the heat loss as the HC stream flows from the original depth (i.e., 3048 m) to the circulation depth. This HC inlet temperature is obtained using the graph in Figure 3.

The results of reducing circulation depth are shown in Figure 9. As expected, the pump power increases linearly with the circulation depth. The WF outlet temperature and thermal recovery initially increase with increased circulation depth but then level off beyond 1000 m to 1500 m. Analyses such as this may be used to determine the optimum circulation depth, which will be primarily governed by the economics of the project.

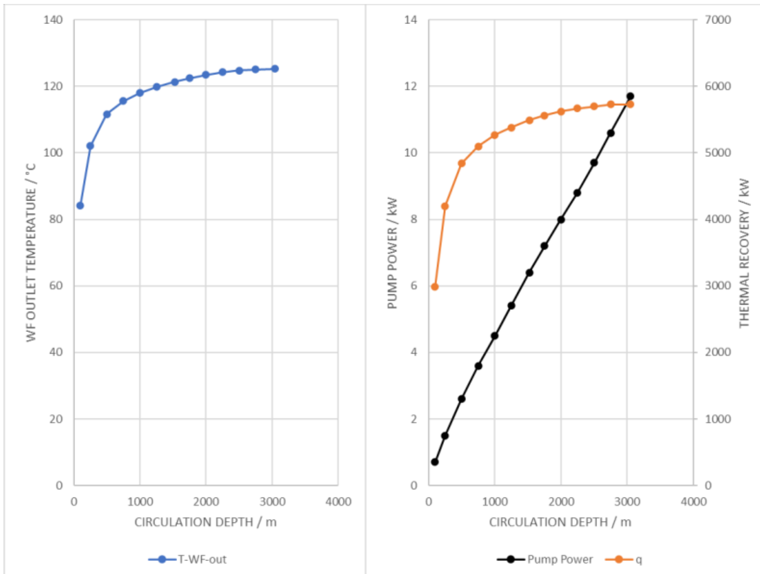

Figure 9: System performance vs. circulation depth.

3.5 WF Flow Rate

Finally, the model is used to examine the effect of WF flow rate on the thermal recovery and pump power. The results are shown in Figure 10.

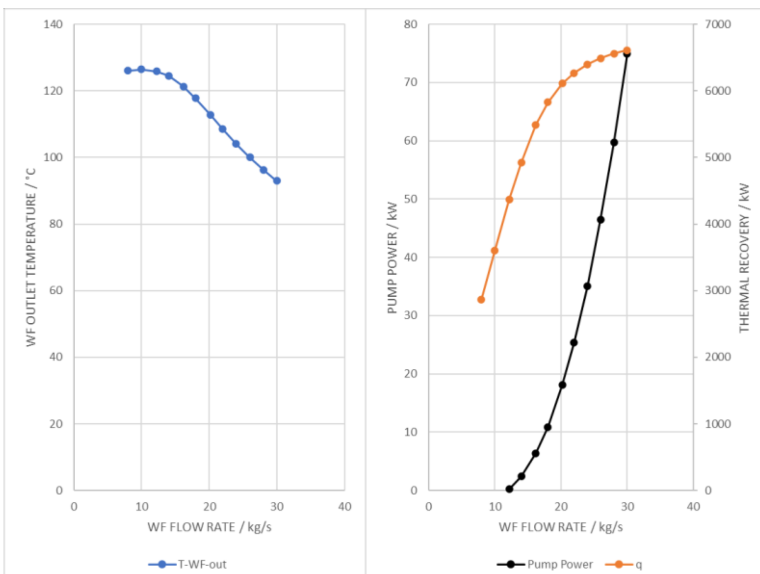

Figure 10: System performance vs. WF flow rate.

This figure shows that increasing WF flow rate will increase thermal recovery at the expense of increased pump power and reduced WF outlet temperature. This suggests that there is an optimum WF flow rate that results in the best combination of thermal recovery, WF outlet temperature and pump power. For example, for electricity production, the thermal efficiency depends on the WF outlet temperature, so having a sufficiently high temperature may be more important than maximizing thermal recovery. The optimum WF flow rate will be different for each project, depending on the project objectives.

Figure 10 also shows that below WF flow rate of 12 kg/s the thermosiphon effect is sufficient to drive the circulation without the need for any circulation pump. In this case, cop will be infinite. However, a pump is still required to start the system and to bring it to steady-state operation. Also, the thermal energy recovery is relatively low at this low WF flow rate.

4. WORKOVER PROCEDURE

Suitable hydrocarbon wells may be re-configured for ACC using the following straightforward workover procedure:

1. Move in with a drilling or workover rig.
2. Rig up and test blowout preventer (BOP).
3. Kill the well.
4. Remove tubing hanger.
5. Unset packer.
6. Remove (pull) existing tubing from the well.
7. Inspect condition of the production casing. Perform any indicated repairs and cleanup operations.
8. Run divider string. Install new casing hanger section for the divider string.
9. Run new tubing with packer. Set packer.
10. Install tubing hanger.
11. Connect WF circulation pump to the wellhead.
12. Unload the tubing to put well in production.
13. Start WF circulation through the well. Wait for WF to warm up to the steady-state temperature.

5. CONCLUSIONS

This paper describes a thermo-hydraulic model developed to analyze a ACC to co-produce geothermal energy from existing hydrocarbon wells. The model has shown the following:

1. Forward circulation, where WF is pumped through the A annulus and returns through the B annulus, shows higher thermal recovery than the reverse circulation. This is due to the counterflow heat transfer arrangement formed between the HC stream and down-flowing WF in A annulus.
2. Insulation of the divider string is essential in improving thermal recovery. Using a composite divider string may be sufficient. Using VIT provides even better thermal recovery but at the expense of increased pump power due to reduced flow area.
3. Most of the heat transfer occurs in the top portion of the well. Therefore, the circulation depth may be reduced to reduce circulation pump power requirement and reduce divider string cost. The optimum circulation depth will be different for each project.
4. Similarly, each project will have an optimum WF flow rate. In general, increasing WF flow rate will increase thermal recovery but at the expense of decreased WF outlet temperature and increased pump power requirement. At low enough WF flow rates, the thermosiphon effect is sufficient to sustain WF flow without the use of a circulation pump (although a pump is required to start the system, and the thermal recovery is relatively low).

Finally, the paper outlines a high-level workover procedure that may be used to re-configure an existing hydrocarbon well for co-production.

NOMENCLATURE

A	area, m^2
c	specific heat, kJ/kg/°C
cop	coefficient of performance
d	diameter
f	friction factor
g	acceleration due to gravity, g=9.81 m/s^2
h	heat transfer coefficient, kW/m^2/°C
k	thermal conductivity, kW/m/°C
L	circulation depth, heat transfer length, m
$\dot{m}$	mass flow rate, kg/s
P	pressure, MPa
$\dot{Q}$	thermal recovery rate, kW
R	heat transfer resistance, °C/kW
T	temperature, °C

UA	overall heat transfer conductance, kW/°C
$\dot{W}$	mechanical or shaft power, kW
z	depth, m
ρ	density, kg/m^3
ϕ	fraction of available thermal recovery
τ	time, s or day

Subscripts

A	A annulus fluid/stream
B	B annulus fluid/stream
c	production casing string
d	divider string
F	flow
f	friction
G	geothermal
g	gravitational
H	hydraulic
HC	hydrocarbon
i	inner or inside
in	inlet
MAX	maximum
o	outer or outside
out	outlet
P	pump
T	tubing fluid/stream
t	tubing string
WF	working fluid

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