Investigating the Causes of Production Decline in ULB-02 Well, Ulumbu Geothermal Field: A Combined Decline Curve Analysis and Reservoir Scaling Simulation Approach

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Abstract. This study examines the declining steam production at the Ulumbu Geothermal Power Plant in East Nusa Tenggara, Indonesia, focusing on the ULB-02 well from 2015 to 2023. Initially, a 5% annual decline in steam output was expected; however, recent data indicates an accelerated decline, likely due to scaling within the wellbore. Scaling reduces steam flow and well productivity, contributing to a significant decrease in wellhead pressure (WHP) and steam flow rate. Decline curve analysis (DCA) shows an exponential decrease in steam output, with projections indicating a reduction to about 12.5 kg/s by 2030, corresponding to a drop in power generation capacity to around 5 MW. To assess the impact of scaling, the study uses TOUGHREACT simulations to model mineral deposition and its effect on wellbore permeability. The results confirm that scaling is a primary factor in the well's declining performance. The study highlights the importance of reservoir management and scaling mitigation strategies to ensure the long-term sustainability of the Ulumbu plant. Recommendations include monitoring wellhead pressure, addressing scaling issues, and implementing periodic interventions to optimize well performance and prevent further output decline. These findings are relevant to other geothermal fields with similar challenges.

Keywords: *production decline, geothermal well, DCA, TOUGHREACT, scaling*

1 Introduction

The Ulumbu Geothermal Power Plant is located in Ponggeok Village, Satar Mese District, Central Manggarai Regency, East Nusa Tenggara Province (Fig.1). It is located approximately 26 kilometers southeast of Ruteng City on the southern part of Flores Island. With an installed capacity of 10 MW, the plant provides electricity to the Ruteng and Labuan Bajo grids, benefitting over 100,000 people (BPS, 2023). This power plant operates as a baseload plant, ensuring a stable electricity supply in East Nusa Tenggara, particularly in areas with power deficits.

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Figure 1. Ulumbu Power Plant Location

The Ulumbu Geothermal Power Plant comprises four units: two condensing units since July 2012 and two back-pressure units since September 2014. However, only the ULB-2 well has been supplying steam to the plant. The wellhead pressure for ULB-2 has gradually decreased since it began operating. This study aims to analyze the decline in well production and reservoir pressure by examining operational data from January 2015 to December 2023.

1.1 Geological Aspect

The Ulumbu geothermal field is located within the Poco Leok volcanic complex on Flores Island, Indonesia. It shows fumarolic thermal manifestations but does not have chloride springs. The up-flow zone is likely below the Poco Rii-Poco Leok caldera, while the outflow zone is suspected to be southwest of this area, near the current production well location.

The Ulumbu geothermal field is characterized by fumaroles and an absence of chloride springs. The main upflow zone is inferred to be beneath the Poco Rii-Poco Leok caldera, with the outflow directed southwest. The geothermal system is hosted within a stratigraphic sequence composed of Tertiary sedimentary basement rocks overlain by Quaternary volcanic units. The Quaternary volcanic units, specifically the QVL, QVM, and QVU, function as the reservoir, cap rock, and surface formation, respectively (Fig.2) [4]. These interpretations are based on analyses of alteration, drilling losses, and cuttings and core data.

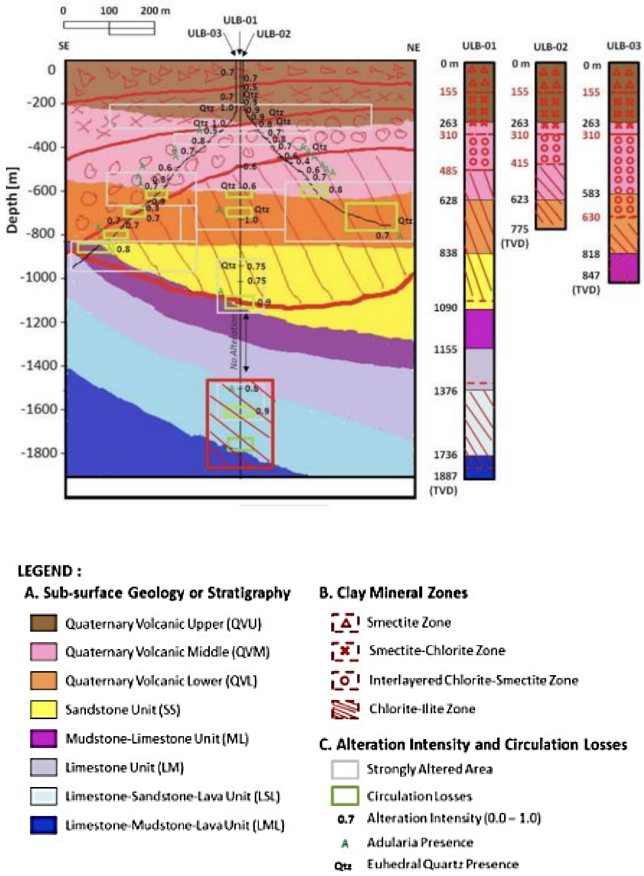

Figure 2. A summary of the drilling data used to infer the reservoir structure, Kasbani (1996) [3]

1.2 Production Well ULB-02

The Ulumbu Geothermal Power Plant began operations in 1994-1995 when three deep wells were drilled in the Wewo block, approximately 100 meters from a fumarole. Of these, one well was drilled vertically and two were drilled at an angle. A reservoir temperature of 240°C was measured, with a productive steam zone found at a depth of around 750 meters. The first exploratory well, ULB-01, penetrated Quaternary volcanic rock formations and Tertiary sedimentary formations, reaching a total depth of 1887 meters. However, ULB-01 was not optimized as a production well due to insufficient steam capacity.

Drilling of well ULB-02, directed northeast, successfully produced dry steam with a capacity of approximately 12 MW, making it the primary source for the Ulumbu Geothermal Power Plant (Fig.3). This well demonstrated stable and efficient steam production during its initial operational phase. Meanwhile, well ULB-03, initially unused, was identified as having the potential to increase steam supply in the future [5]. This well can produce dry steam with a manageable level of non-condensable gases.

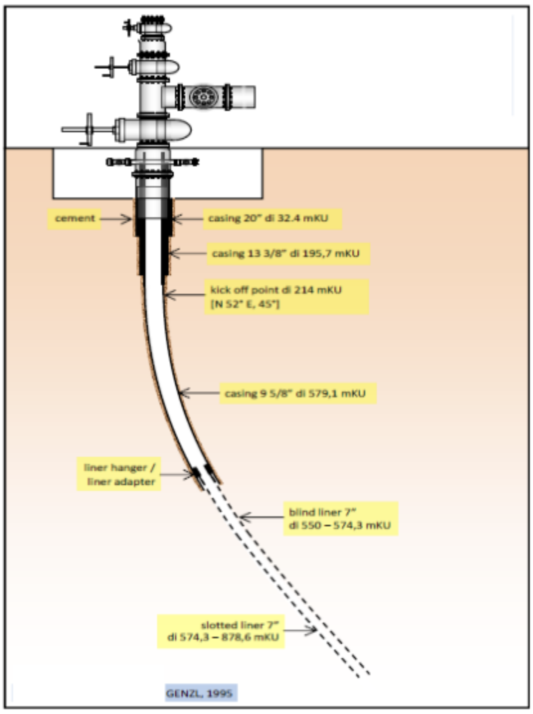

Figure 3. Production Well ULB-02 Profile

Well ULB-02 plays a crucial role in supplying steam to Ulumbu power plant units 1, 2, 3, and 4, each with a capacity of 2.5 MW. To assess the well's performance, testing was conducted in November 2011 using two different methods. Method 1 (Setting I): The well was gradually opened, starting at high wellhead pressure (WHP) and decreasing in stages to low WHP. Pressure settings used were 20, 17.5, 15, 12.5, and 10 barg. Method 2 (Setting II): The well was opened in the opposite order, starting at low WHP and increasing to high WHP. Pressure settings used were 10, 12.5, 15, 17.5, and 20 barg. Operational Setting: For the actual operation of the Ulumbu power plant, Setting II is used for wellhead pressure (WHP) settings [6].

1.3 Operational History

Well ULB-02 became the primary steam supplier for the Ulumbu Geothermal Power Plant, which had a capacity of 4 x 2.5 MW on a 20 kV distribution network. However, current operational conditions have deteriorated, with only three generating units operating and one on standby, due to a decline in steam capacity from well ULB-02. In 2020, a model predicted a decline in well production of 5.4% per year (exponential) and 3.4% per year (harmonic) [6]. This condition will undoubtedly affect the operation of the Ulumbu Power Plant in supplying electricity to the Flores region.

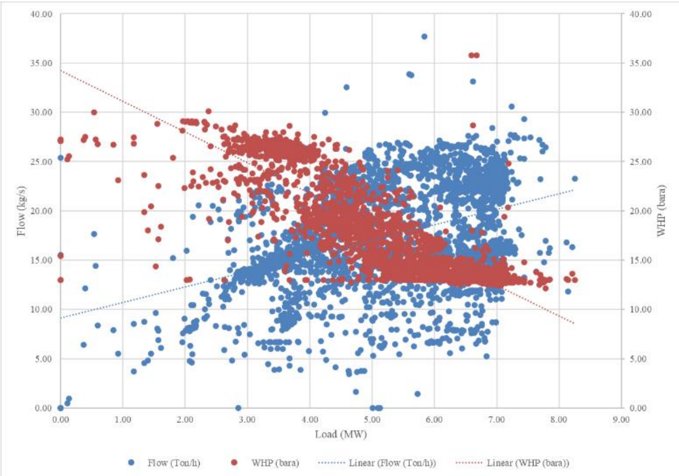

Figure 4. Load, Flow Rate and Well Head Pressure of ULB-02

Currently, Ulumbu Geothermal Power Plant operates three generating units. Units 1 and 2, designed with backpressure capability, are operated on a weekly alternating basis for flexibility and black start capability. Units 3 and 4 operate continuously. This configuration yields a total power output of 7 MW, with an average wellhead pressure (WHP) of 13 barg and a mean steam flow rate of 17.13 kg/s. Figure 4 presents the current operating conditions, including steam flow rate and wellhead pressure, while the wellhead pressure profile from 2015 to 2023.

2 Decline Curve Analysis

Decline curve analysis is a commonly utilized technique for estimating recoverable reserves in a field and forecasting future production performance using historical data. This method also provides insights into the field's economic feasibility and forecasts how production will change based on established trends.

Production forecasting for Well ULB-02 was carried out utilizing decline curve analysis, with data collected over a nine-year period from 2015 to 2023.

Beyond reserve estimation, decline curve analysis can be applied to predict pressure decline when a well or reservoir is produced at a constant flow rate. This analysis enables forecasting future production rates, allowing for the planning of infill drilling to maintain the field's overall production in line with targets. The fundamental equation used in decline curve analysis is the Arps equation, which serves as the cornerstone for modeling production decline [1][2].

$$q(t) = \frac{qi}{(1 + b\ Di\ t)^{(1/b)}}$$

The following variables are used in the equation:

q(t) : The mass flow rate at a specific point in time (t)

qi : The initial fluid production rate at the beginning (when t = 0)

b : A dimensionless constant known as Arps' constant or exponential

Di : The initial decline rate, which represents how quickly the production rate decreases over time ($\frac{-\,dq(t)}{dt/q(t)}$)

Based on the b value, the equation can be classified into three types of decline: exponential, harmonic, and hyperbolic. Examination of the Arps equations reveals the critical importance of the decline exponent, b, which was found to be dependent on fluid parameters and production conditions and influences the degree of curvature of the decline [1]. Arps proposed that the b-values range from zero to one, with no mention of the possibility of b>1.

Exponential decline

$$q(t) = \frac{qi}{e^{(Di * t)}} = qi\ e^{(-Di * t)}$$

Harmonic decline

$$q(t) = \frac{qi}{(1\ +\ Di\ t)}$$

Hyperbolic decline

$$q(t) = \frac{qi}{(1 + b\ Di\ t)^{(1/b)}}$$

3 Static Pressure and Decline Curve Analysis

It is crucial to monitor static pressure and production fluid flow rate in the field to assess the behavior of a geothermal field. Analyzing decline curves is a common method used for this assessment. To conduct decline curve analysis, it is essential to have data on static wellhead pressure and continuous fluid production flow rate. The analysis is based on an empirical gas equation that is often used in wells in the Geysers Field.

$$W = C_o\ ({p_r}^2 - {p_f}^2)^n$$

The equation used to calculate production rate in this field involves several factors: mass flow rate, static wellhead pressure, flowing wellhead pressure, and two constants (Co and n). These constants can change over time, so it's important to regularly test the well's deliverability to update their values.

While the flowing wellhead pressure (p) will decrease during production, the other constants (Co and n) remain relatively stable. Assuming they stay constant, we can use their initial values to estimate production rates. However, production rates can fluctuate depending on the operating conditions of the field. To accurately measure the decline in production, we need to normalize the flow rate at a specific pressure level.

The method we're using to calculate production rates is based on an updated equation developed by Acuna. This equation is specifically designed for analyzing geothermal fields that produce a lot of steam, like the Ulumbu field. The equations used for analyzing these types of geothermal wells are as follows:

$$W = C_{wb}\ ({p_{rg}}^2 - \frac{2\ v_{rg}\ p_{rg}\ W}{PI})^{0.5}$$

The equation for determining the reservoir decline rate is as follows:

$$W = {C_{wb}}^2\ ((\frac{p_{rg}}{A} - \frac{{p_f}^2}{{C_{wb}}^2})^{0.5} \text{-} \frac{v_{rg}}{PI}\ p_{rg})$$

$$p_{rg} = p_r\ ({p_r}^2 - {p_f}^2)^n$$

$$v_{rg} = v_r \left(1 - \frac{CgH}{2}\right)$$

vrg = vr * (1 - (CgH / 2))

A = 1 / ((1 / Cwb)^2 + (vrg / PI)^2)

The following variables are used in the equation:

PI	: Well productivity index	H	: Elevation difference
p_{rg}	: Gravity-corrected (P_{res})	C	: Steam density constant pressure
v_{rg}	: Kinematic viscosity	g	: Gravitational constant
C_{WB}	: Wellbore coefficient	W	: Mass flow rate

Based on field observations, the C_{WB} and PI coefficients remain relatively stable unless there are alterations in the wellbore's geometry or the reservoir's characteristics, such as permeability or steam quality. Therefore, a change in these parameters indicates potential obstructions or issues within the field. Prompt action can be taken to address these problems and maintain optimal production.

4 Scaling Simulation

A comprehensive analysis of scaling decline will be conducted using numerical simulations with TOUGHREACT. Input data will include Production Test Summary (PTS) results, geochemical data, petrophysical properties of the reservoir rock, well geometry, and well operating conditions [7]. The simulation results will provide insights into scaling mechanisms, scaling location and severity, and the mineral composition of the scale. These simulation results will serve as a basis for evaluating various effective mitigation strategies.

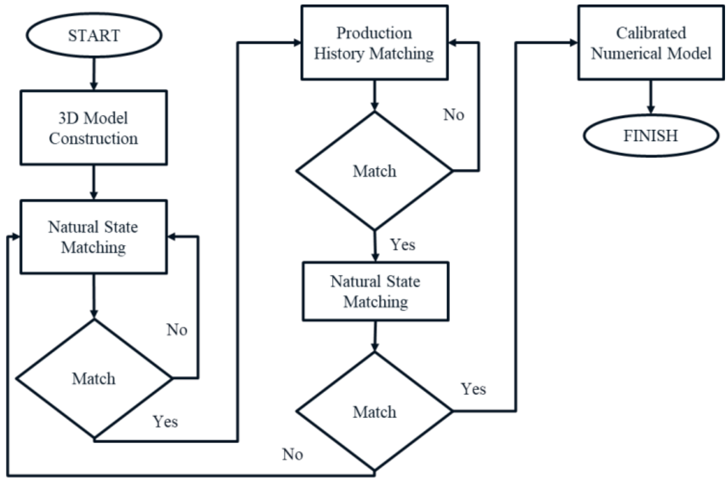

Figure 5. Scaling Simulation Flowchart

The TOUGHREACT flowchart outlines the process of constructing and calibrating a numerical model to simulate the behaviour of a geothermal system (Fig.5), specifically well ULB-2. The process begins with creating a 3D geological model of the reservoir surrounding well ULB-2, followed by adjusting the model to match the initial conditions of the reservoir before production. Subsequently, the model is calibrated against historical production data from well ULB-2 through an iterative process. This involves adjusting model parameters such as permeability, porosity, and temperature until the simulated production from the model matches the actual production data from well ULB-2. Once a good match is obtained, the calibrated numerical model can be used for various analyses, such as predicting future production of well ULB-2, evaluating optimal field development strategies, or analyzing the impact of changes in operating conditions on well performance.

5 Implementation

A case study was conducted on well ULB-02 to investigate its production performance over a nine-year period spanning from 2015 to 2023. Production data from the well was utilized to construct a decline curve. The graph flow rate vs WHP shows the relationship between the flow rate of fluid produced from the well and the pressure at the wellhead. This helps visualize how the production rate changes as the pressure decreases over time.

The relationship between wellhead pressure (WHP) and flow rate in geothermal systems typically follows an inverse trend, where a decrease in pressure leads to an increase in flow rate. However, this correlation is not always observed in the

Ulumbu geothermal wells (Figure 6). For example, in 2018, despite a decrease in WHP from 15 bar to 10 bar, the flow rate increased from 15 tons/hour to 20 tons/hour. This suggests that technical interventions, such as acidizing or well cleaning, which improve permeability, can allow for higher fluid flow even when pressure decreases. Similarly, in 2020, although WHP dropped to 5 bar, the flow rate remained stable at 10 tons/hour, indicating effective reservoir management and pressure control.

In contrast, in 2022, a sharp decline in WHP to 2 bar was followed by a drop in flow rate to 5 tons/hour, indicating potential issues such as scaling or a decline in local permeability. These fluctuations highlight the importance of monitoring pressure and flow rate to identify operational problems such as scaling. Despite the expected inverse relationship between pressure and flow rate, interventions and reservoir conditions can result in varying outcomes, underscoring the need for tailored management strategies to maintain production performance in geothermal wells.

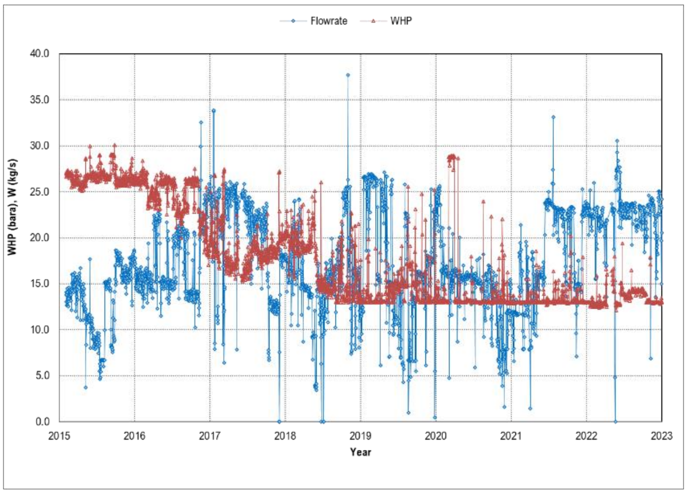

Figure 6. Flow Rate vs Well Head Pressure (WHP) ULB-02 period 2015 - 2023

The graph, as shown in Figure 7, shows the pressure and flow rate dynamics of three wells at the Ulumbu geothermal field: ULB-02 (production well), ULB-01, and ULB-03 (monitoring wells). ULB-02 initially had a stable wellhead pressure (WHP) of 27-28 bar, but it decreased significantly to below 20 bar, with the pressure later maintained at 13 bar to stabilize production flow. In contrast, ULB-01 remained stable around 28 bar, indicating minimal impact from production, while ULB-03, located near ULB-02, showed significant pressure fluctuations in 2019, likely due to the influence of ULB-02's production. After acidizing, ULB-03's pressure recovered, and permeability improved.

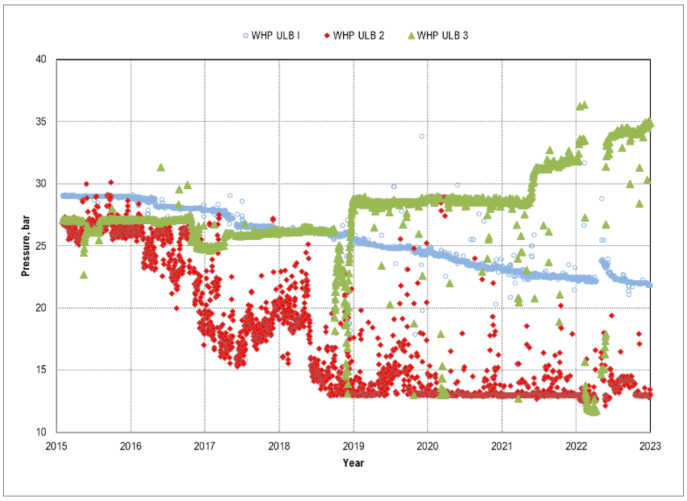

Figure 7. Pressure of Reservoir vs WHP (2015-203)

These trends highlight the challenge of maintaining reservoir stability. While ULB-02's pressure declines due to production, data from the monitoring wells ULB-01 and ULB-03 are critical to ensure sustainable production. The acidizing of ULB-03 helped stabilize pressure, but long-term effects on injectivity and permeability should be closely monitored. This underscores the importance of balancing production with proper reservoir management to prevent excessive pressure depletion.

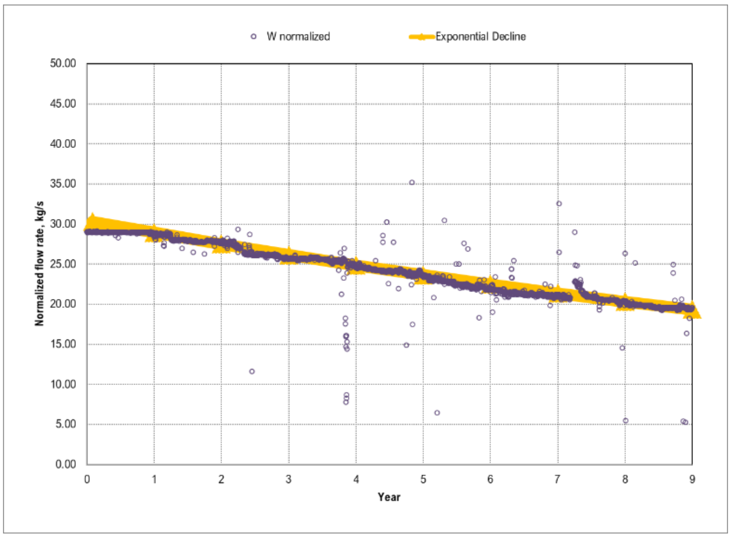

Figure 8. Decline Curve Model With Normalized Flow Rate Calculation

The normalized flow rate in the graph exhibits an exponential decline, indicating that the production from the geothermal system is decreasing at a consistent rate over time. This type of decline suggests that as the reservoir is being continuously utilized, the ability to produce steam or fluid diminishes at a steady percentage annually. The flow rate starts at a higher value and then gradually decreases, following an exponential curve, as shown as in Figure 8. This behavior typically reflects the natural depletion of the reservoir's energy output as it continues to produce over time, with the rate of decline remaining relatively constant unless significant changes in reservoir pressure or interventions occur. As seen in the graph, the flow rate normalizes over time, which suggests a predictable decrease in steam production, with future projections indicating a significant reduction in output, consistent with the expected behavior of geothermal reservoirs under continuous exploitation.

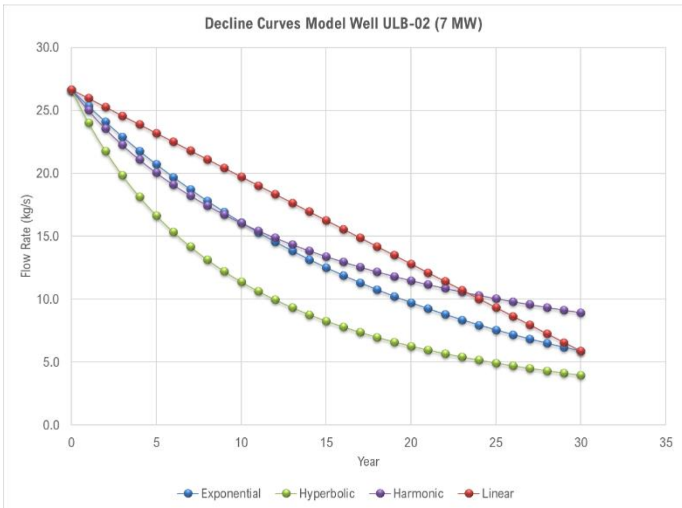

Figure 9. Decline Curve Model ULB-02

The exponential decline model, with a decline rate of 5% per year, shows a consistent and predictable decrease in production (Figure 9). By 2030, the steam flow rate is expected to reach approximately 12.5 kg/s, equating to around 5 MW of power. This model assumes a steady decline in flow rate, typically seen in systems where the reservoir conditions remain relatively stable over time, without significant intervention. In contrast, the harmonic decline model shows a steeper initial decline of about 6.6% per year, which slows over time, often due to natural reservoir adjustments. This model indicates that production will decrease more quickly at first but will stabilize as the reservoir responds.

6 Conclusion

Based on the decline curve analysis of ULB-02, the data shows a stable decrease in wellhead pressure (WHP) over time, following an exponential decline model with a decline rate of approximately 5% per year. By 2030, the steam flow rate is projected to decrease to around 12.5 kg/s, equivalent to 5 MW of power, reflecting the predicted and stable decline in production. This decline indicates that while pressure and production gradually decrease, the system can still operate at a lower capacity according to the projected decline pattern.

The main cause of the production decline in ULB-02 is suspected to be scaling, or the formation of mineral deposits inside the wellbore. Scaling can significantly reduce well productivity by obstructing steam flow and causing additional pressure loss. This phenomenon aligns with the observed exponential decline in ULB-02, where scaling typically leads to a progressive reduction in well production capacity, reflected in the ongoing decrease in steam output.

To validate this hypothesis, a numerical simulation using TOUGHREACT software will be conducted. This simulation will model the scaling process, including the formation of specific mineral deposits and their impact on wellbore permeability. By comparing the simulation results with the observed production decline, we can strengthen the correlation between scaling and the decline in steam production.

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