Thermo-Hydrodynamic Numerical Modeling of the Hêtin-Sota Artesian Geothermal Well (Benin)

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ABSTRACT: Benin's artesian groundwater resources are still underutilized and therefore do not yet contribute fully to the country's socioeconomic development. This is the case with the Hêtin-Sota thermal spring, which appeared following drilling in 1956. In order to assess the Hêtin-Sota spring with a view to developing it, it is necessary to know the values of certain fluid parameters (pressure and temperature) that are not available in the literature or in the archives of Benin's Directorate General of Water (DGEau). These include the temperature and static pressure values in the reservoir at this location, as well as the pressure value at the head of its artesian thermal well, given that the temperature value at the ground surface (T_{ground}=53°C) is known. This work provides an in-depth study of the different stages through which the geothermal fluid circulates and the interactions between them. The code developed during this study solves the simplified Navier-Stokes equations, the heat equation, and the momentum equation using the Matlab language. This code confirms the temperature (T_{res}=66.76°C) and static pressure (p_{res}=58.38 bar) values in the reservoir at this location, as well as the head pressure (p_{head}=15.62 bar) value of the thermal artesian well. Validation of this code shows that in the Hetin-Sôta artesian and thermal well; the simulations are in good agreement with the drilling pressure logs and geothermal fields. The temperature above ground, i.e., at the top of the Hêtin-Sota artesian and thermal well, is 53°C, which is between 30°C and 100°C, and the depth of the well-being 417 m, between 400 and 2000 m, the geothermal energy from this well can be used to develop agricultural land in the Hêtin-Sota area, which is part of the Ouémé Valley in Benin, ranked as the second richest valley in the world after the Nile in Egypt.

KEYWORDS: simulation, geothermal energy, groundwater, artesian, pressure, temperature, MATLAB.

1 INTRODUCTION

The subsoil is characterized by its multifunctionality, associated with its properties as a container, a source of content, and a porous space. It offers numerous resources (hydrocarbons, minerals, drinking water, heat reservoirs) and serves as a basis for human settlement [1]. Indeed, while its exploitation is responsible for the depletion of resources, it remains the place where the solution to this problem can be found [2-3].

Groundwater thermal springs represent a natural heritage of great importance and appear to be a potential driver of economic and social development, as several case studies in Africa have shown [4]. In Europe, hydrotherapy and tourism are more developed thanks to these resources. In Italy, 70% of the population uses these resources to treat skin disorders and respiratory problems [5]. In France, thermal spas create an economic base by providing more than 100,000 jobs and generating more than €690 million in indirect spending per year [6]. In the Americas, particularly in Peru, local authorities preserve thermal springs by incorporating traditional knowledge into legal frameworks in order to prevent overexploitation and ensure their sustainability [7]. In Asia, specifically in Indonesia, thermal waters are perceived as sacred sites housing the spirits of ancestors, requiring rituals to obtain their blessings [8]. In contrast, in Africa, these resources remain less exploited and less valued due to inadequate regulation and infrastructure problems [9]. In the Republic of Benin, specifically in the municipality of Dangbo, the Hêtin-Sota thermal spring lacks specific regulations due to its regulation. As a result, the development of this natural resource could be an important lever for economic and social development, provided it is carried out in a fair and sustainable

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manner [10]. Thermal springs offer interesting potential for the development of agriculture, tourism, transportation, hotels, restaurants, energy, etc. Their development could contribute to improving the living conditions of local populations, diversifying economic activities, and preserving the environment, in line with sustainable development objectives [11]. In light of the above, the purpose of this study is to examine the parameters that could limit the use and sustainable management of the Hêtin-Sota thermal spring in the municipality of Dangbo in the Republic of Benin, focusing in particular on changes in pressure and temperature along the artesian thermal production well on the site.

2 MATERIALS AND METHODS

2.1 PRESENTATION OF THE STUDY SITE AND HISTORY OF THE ARTESIAN AND THERMAL WELL AT HÊTIN-SOTA

2.1.1 PRESENTATION OF THE STUDY SITE

The study site is located in the village of Hêtin-Sota, in the Késsounou district of the Dangbo commune. The Dangbo commune is situated in the Ouémé Department, between 6°32' and 6°39' North latitude and between 2°28' and 2°34' East longitude. Covering an area of 149 km², it is bordered to the north by the Adjohoun commune, to the south by the Aguégués commune, to the east by the Akpro-Missérété commune, and to the west by the Sô-Ava commune. Administratively, the Dangbo commune is subdivided into seven (7) districts, which comprise fifty (50) administrative villages. The Késsounou district includes six (6) villages, one of which is Hêtin-Sota. The village of Hêtin-Sota is bordered to the north by the village of Dèwèmè-Daho (district of Houédomey), to the south by the village of Hêtin-Gléhoué (district of Késsounou), to the east by the village of Tovè (district of Dangbo) and to the west by the Ouémé river. The Hêtin-Sota geothermal borehole is located at the edge of the access road to the village and at the entrance to the towns. The borehole's geographic coordinates are 2.50396 E and 6.58789 N. The borehole site is located on the left bank of the Ouémé River, 190 meters from the river. Figure 1 shows the geographic location of the Hêtin-Sota geothermal borehole in the municipality of Dangbo, Benin.
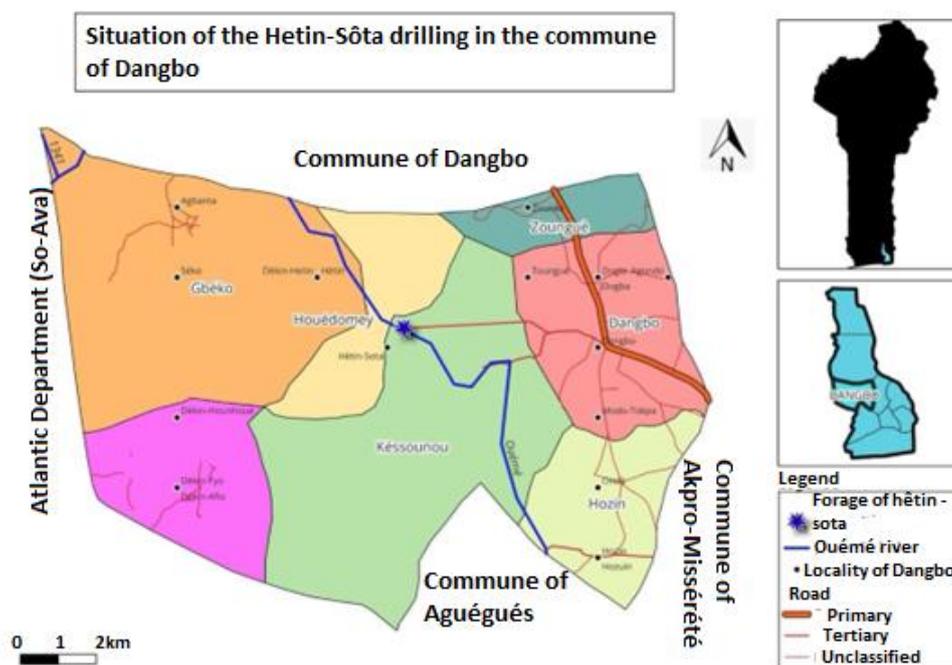

Fig. 1. Geographical location of the Hêtin-Sota artesian and thermal well in the municipality of Dangbo.

Source: IGN-Benin, 2024.

2.1.2 HISTORY OF THE ARTESIAN AND THERMAL WELL AT HÊTIN-SOTA

The drilling was carried out in 1956 by a Canadian mission that had gone to the area to carry out earthworks, including the removal of materials. Having noticed the lack of drinking water in the area, the Canadian mission decided to drill a well there. Two attempts were unsuccessful before a third attempt resulted in this artesian thermal well. This third attempt was made after consulting the fetish "Dossouwè.". In 1956, in addition to the hot water drilling head, related infrastructure was also built. This included gender-specific toilets and concrete swimming pools. Powered by geothermal drilling, all of this infrastructure was equipped with pipe networks for water supply and drainage. Both the well and the related infrastructure were fully controlled. No measures were taken to ensure proper management; everything was used free of charge. In 1970, the well broke down and was repaired in 1971. By that year, the toilets and swimming pools were no longer functional and were not repaired. Then in 1990, it broke down again and the drill head also failed. It was then rehabilitated in 1992 (Figure 2). This rehabilitation was extended to include the construction of other related infrastructure consisting of a distribution network for untreated thermal water. This included the metal tower on the site and four standpipes to serve the neighborhoods of Dogodo, Tchintchinmè, Zounkpa, and Gléhoué. This time, the drainage pipe and the head were replaced. Following this rehabilitation, an 11-member committee was set up to manage the borehole and the new infrastructure. However, part of the population was opposed to this.

Fig. 2.   Status of Fountains projects completed in 1992.

Source: Dangbo Town Hall, 2024.

Thus, by the 2020s, neither the castle nor the standpipes were functional. The standpipe located within the grounds of the Hêtin-Sota primary school had collapsed; the pipes at the water tower and the wellhead were also leaking, and the wellhead was flooded with stagnant water, posing a danger to the population. Concerned about the safety of the population, the Dangbo Town Hall rehabilitated the wellhead, which was raised, and built a footbridge on the site to facilitate access for the population and tourists. Figures 3 and 4 below show the situation of the geothermal well in 2018 (before the City Council's intervention) and in 2023 (after the City Council's intervention).

Fig. 3.   View of the drilling and related infrastructure in 2018.

Source: Dangbo Town Hall, 2024.

Fig. 4.   View of the drilling and related infrastructure in 2023.

Source: Dangbo Town Hall, 2024.

2.2   DESCRIPTION OF THE PROBLEM

The physical model of a thermal artesian well is generally considered to be a vertical circular pipe with liquid flowing in the deep zone, which changes phase in the upper zone due to the reduction in pressure and static temperature. A two-phase zone (liquid and vapor) is formed above a certain point with an increase in mixing velocity. The analysis of two-phase flow inside a thermal artesian well requires the correct calculation of pressure, temperature, enthalpy, heat flux, and velocity profiles along the well, as well as knowledge of the thermodynamic properties of the fluid. These parameters can be calculated from energy

governing equations using numerical schemes that represent the complexity and multidimensionality of two-phase flows. Although many simulators for modeling fluid and heat flow in thermal artesian wells have already been developed, their predictive ability to match field-measured data has only been partially successful. Figure 5 presents the physical representation of the problem.
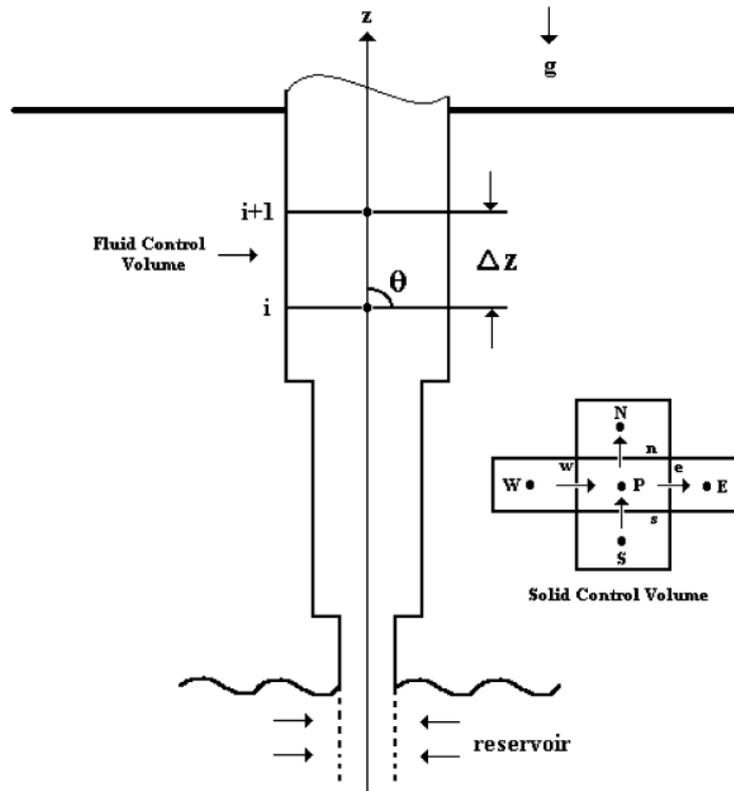

Fig. 5.   Physical representation of the problem [17].

2.3   THE DATA NEEDED TO MODEL A DRILLING OPERATION

Data concerning the geometry and hydrodynamics of the artesian and thermal borehole are summarized in Table 1 and mainly concern technical data from the artesian and thermal borehole drilled in the village of Hêtin-Sota, provided by the Benin Water Authority (DGEau).

Table 1.   Geometric characteristics and hydrodynamic parameters of the Hêtin-Sota artesian and thermal well.

Geometric characteristics and hydrodynamic parameters of the Hêtin-Sota artesian and thermal well	
Drilling depth H (m)	417
Roof depth (m)	392
Thickness of the tank e_{res} (m)	25
Drill hole diameter D (m)	0.200
Flow rate Q (m³/h)	60.16
Permeability (m/s)	10-5
Acceleration of gravity g (m/s² or N/kg)	9.81
Fluid temperature at the ground surface (°C)	53

Source: DGEau, 2024.

LITHOLOGY OF HÊTIN-SOTA

The different horizons of the drilling profile are presented in Table 2.

Table 2. Profile of the Hêtin-Sota thermal borehole.

Upper depth (m)	Minimum depth (m)	Lithology	Description
0	47	Clay	Clay
47	75	Fine sand	Fine sand interbedded with sandy clay
75	104	Clay sand	Clay sand + fine sand + loamy sand
104	284	Clay	Clay + clayey sand loam
284	288	Clay	Gray-blue clay
288	298	Marne	Dark sandstone and blackish gray
298	368	Clay	Layered gray clay
368	392	Limestone	Calcareous clay and sandy loam
392	398	Limestone	Marble and white limestone
398	417	Lmestone	Cracked whitish shell limestone

Source: DGEau, 2024.

2.4 FORMULATION OF EQUATIONS IN DRILLING

The code is mainly based on solving simplified Navier-Stokes equations, the heat equation, and certain parietal closure laws. As a first step, the system of equations is solved using the homogeneous model, which assumes that the velocity of the liquid and that of the vapor produced are equal. This assumption will be corrected later by a slip ratio factor. The homogeneous model allows us to consider the two-phase mixture as a single phase by replacing the quantities of this phase with those of the mixture. In all of the following, discretization is performed using the finite difference method with an explicit scheme.

2.4.1 MOMENTUM EQUATION WITH AN EXPLICIT SCHEME

The momentum equation allows us to calculate pressure by calculating hydrostatic pressure and pressure losses. Pressure losses are calculated using the following formula:

$$\frac{dp}{dz} = -\frac{\lambda * L * \rho * U^2}{2.D_h} \tag{1}$$

with:

dp/dz: pressure variation per unit length (linear pressure);
λ: pressure loss coefficient (or friction coefficient);
L: Length of the pipe;
ρ: Density of the fluid;
U: Average velocity of the fluid in the pipe;
D_h: Hydraulic diameter of the pipe.
dz: Space variation (or distance between grid points);
dp: Pressure variation.

After discretization using the finite difference method with an upstream offset scheme, we obtain the following expression:

$$dp_{drillng}(k-1) = p_{drilling}(k) - \rho * g * dz - \frac{\lambda * L * U^2}{2.D} \tag{2}$$

$dp_{drilling}$ (k-1): The pressure drops between point (k-1) and point k;
$p_{drilling}$ (k): The pressure at the end of the element, at point k;
$-\rho.g.dz$: The head loss term related to elevation, representing the pressure difference due to the change in altitude (dz), calculated according to Bernoulli's equation;
$-(\lambda.L.\rho.U^2)/(2.D)$: The head loss term related to friction in the pipe.

Here we assume that $p_{drilling}$ (1) corresponds to the pressure at the bottom of the borehole and p_drilling (nboring) to the pressure at the top of the borehole.

The initialization of the pressure, i.e., the pressure field at the initial moment, is calculated by the hydrostatic pressure, and we assume that at the initial moment, only liquid water exists in the well.

$$p_{1drllng}(k-1) = p_{1drilling}(k) - \rho_l.g.dz \tag{3}$$

$p_{1drilling}$ (k-1): Pressure at the lower point;
$p_{1drilling}$ (k): Pressure at the upper point,
ρ_l: Density of the liquid fluid.

The pressure at the bottom of the well is calculated by calculating the pressure in the reservoir:

$$p_{Ndrilling} = p_{res}(n_{res}) \tag{4}$$

2.4.2 HEAT EQUATION

The heat equation allows us to model the temperature field in the fluid domain:

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial z} = D\frac{\partial^2 T^2}{\partial z} - h * \left(T(z) - T_p(z)\right) \tag{5}$$

∂T/∂t (Accumulation term/time variation): describes the rate at which temperature T changes over time t at a fixed-point z;
U ∂T/∂z (Convection term): represents heat transport due to fluid (or medium) movement at speed U along the z direction. If U is positive, heat is transported in the direction of increasing z.
D (∂² T/∂z²) (Conduction/diffusion term): describes the propagation of heat by thermal conduction (diffusion).
D: The thermal diffusivity coefficient of the material. This term tends to equalize the temperature in the medium.
-h* (T (z) -Tp (z)) (Source/sink term, often related to convection or surface exchange): represents heat exchange between the main medium (at temperature T (z)) and a surrounding medium (at temperature Tp (z));
h: A heat exchange coefficient (or similar parameter).

After discretization and using an explicit centered scheme, we obtain:

$$T^{N+1}(k) = T^N(k) - U*\frac{dt}{dz}\left(T^N(k+1) - T^N(k)\right) + D*\frac{dt}{dz^2}\left(T^N(k+1) - 2T^N(k) + T^N(k-1)\right) - h* \tag{6}$$
$$dt*(T^N(k) - T^{pN}(k))$$

$T^{N+1}(k)$ $T^{N+1}(k)$: The temperature at grid point k at time N+1;

$T^N(k)$ $T^N(k)$: The temperature at grid point k at time N;

$U*\frac{dt}{dz}\left(T^N(k+1) - T^N(k)\right)$: Convection term. It models heat transfer due to fluid motion;

$D*\frac{dt}{dz^2}\left(T^N(k+1) - 2T^N(k) + T^N(k-1)\right)$: A diffusion term that models heat dispersion through the medium;

$T^{pN}(k)$: Ambient temperature at grid point k at time N

dt: Variation de temps.

2.4.3 PHASE CHANGE

The condition T (z) >T_{sat} (p (z)) means that boiling begins when the liquid substance reaches a temperature T (z) higher than its saturation temperature T_{sat} at a given pressure p (z). In other words, boiling occurs when the temperature of the liquid exceeds the temperature at which its vapor pressure equals the ambient external pressure.

HYPOTHESES

It is assumed that the temperature (T) of the fluid as a function of time (t) and position (z) is equal to the saturation temperature (T_{sat}) during boiling:

$$T(t,z) = T_{sat}\big(p(t,z)\big) \tag{7}$$

A term is then added to the heat equation, the heat flow from the phase change:

$$Q_{chang\ phase} = G * h_{lg} * \left(\frac{dx}{dz}\right) \tag{8}$$

Avec:

$$G = Q * \big(\rho_g * x + \rho_l * (1-x)\big) * \pi * R^2 \tag{9}$$

$Q_{phase\ change}$: Heat flow associated with phase change (in watts)
h_{lg}: Latent energy of phase change (latent heat);
Q: The density of the fluid in the context of phase change;
ρg: The density of the gas phase;
ρl: The density of the liquid phase;
x: The vapor fraction (or phase fraction);
R: The radius of the cross section.

Since the temperature is equal to the saturation temperature, the heat equation becomes:

$$\frac{\partial T}{\partial t} + U * \frac{\partial T}{\partial z} = D * \frac{\partial T^2}{\partial z^2} - h * \left(T_{sat}\big(p(z)\big) - T_p(z)\right) - G * \frac{h_{lg}}{\rho c_p} * \frac{dx}{dy} \tag{10}$$

Thus,

$$G * \frac{h_{lg}}{\rho c_p} * \frac{dx}{dy} = -U * \frac{\partial T}{\partial z} + D * \frac{\partial T^2}{\partial z^2} - h * \left(T_{sat}\big(p(z)\big) - T_p(z)\right) \tag{11}$$

After discretization, we have:

$$x_N(k+1) = x_N(k) - dz * G * h_{lg} \tag{12}$$
$$* \Big(U * dz * \big(T_N(k+1) - T_N(k)\big) + D * dz^2\big(T_N(k+2) - 2 * T_N(k+1) + T_N(k)\big) - h$$
$$* \big(T_N(k) - T_{pN}(k)\big)\Big)$$

$x_N(k+1) = x_N(k)$ (Time term) which represents an explicit approximation of the time derivative. It uses the temperature value at time (k) to calculate the value at time (k+1);

$D * dz^2\big(T_N(k+2) - 2 * T_N(k+1) + T_N(k)\big)$ (Diffusion term) which represents thermal diffusion. It uses an approximation of the second spatial derivative, and it is necessary to know the values at time points k and k+1;

$h * \big(T_N(k) - T_{pN}(k)\big)$ (Convection term) which represents convection. It uses the temperature difference between the point in space and its environment to estimate the heat lost by convection.

$U * dz * \big(T_N(k+1) - T_N(k)\big)$ (Heat generation term) which represents heat generation. It depends on heat flux and thermal energy.

The equation can be simplified by grouping similar terms. For example, the terms $T_N(k+1)$ and $T_N(k)$ can be grouped together, which simplifies the expression of $T_N(k+1)$.

We use the expression of the homogeneous model of the volume fraction:

$$R_g(k) = x(k)\Big(x(k) + \rho_g * \rho_l * \big(1 - x(k)\big)\Big) \tag{13}$$

2.5   MODEL CODE DESCRIPTION

The code developed in this study uses the equations formulated in the previous section and uses the Matlab language to code them.

The code begins with:

- Start of the program;
- Read all problem parameters;
- Initialize variables;
- Calculate pressure in the reservoir;
- Start a time loop:

  o Start a loop on the depth z of the borehole;

  ↳ Calculate all the properties of the mixture;
  ↳ Calculate all the pressure loss coefficients and the convective heat transfer coefficient of the liquid;
  ↳ Calculate the pressure in the borehole using the hydrostatic pressure and the pressure losses of the mixture;
  ↳ The temperature will be equal to the saturation temperature, which is calculated from the pressure;
  ↳ If the temperature is lower than the saturation temperature, then:

    ▪ If the vapor pressure is greater than 0, which means that the fluid was boiling and consists of vapor and liquid, then:

      ✓ Calculates the convective heat transfer coefficients of the mixture;
      ✓ The transported heat flux (which takes into account advection, diffusion, and heat losses) is used to calculate the new mass title;

    ▪ If the vapor title is equal to 0, then the fluid is entirely composed of liquid, and the heat flow transported is used to further heat the liquid.

  ↳ If the temperature is greater than or equal to the saturation temperature;

    ▪ If the vapor content is between 0 and 1, then the temperature becomes equal to the saturation temperature and the heat flow transported contributes to the phase change;
    ▪ If the vapor content is equal to 1, then the fluid is entirely in the vapor phase and the heat flow is used to heat the vapor;

  o End of the loop on the depth z of the borehole;
  o Calculation of boundary conditions;
  o Verification of the convergence condition;

- End of the time loop;
- Writing the result files
- End of the program

3   RESULTS

In this section, we will present the results:

- of the calculation of the fluid temperature in the reservoir based on the temperature at the wellhead and the depth of the well;
- of the calculation of the fluid density as a function of temperature;
- of the calculation of the pressure in the reservoir and at the wellhead;
- the results obtained using the code developed during this work:

In all of the following, we assume that initially there is only pure liquid water in the well and reservoir, and we initialize the pressure field with hydrostatic pressure.

3.1 CALCULATION OF THE TEMPERATURE OF THE FLUID IN THE RESERVOIR

The reservoir temperature was not available in the data obtained from the Directorate General of Water. It was therefore estimated based on the temperature at the top of the borehole and the depth of the borehole, taking into account the average geothermal gradient of the earth [12].

$$g_G = \frac{\Delta T}{\Delta Z} = 0.033 \; {}^{\circ}C/m \tag{14}$$

$$T_{res} = T_{soil} + (g_G * H) \tag{15}$$

Where:

g_G: Geothermal gradient
ΔT: Temperature variation
ΔZ: Altitude variation
T_{res}: Temperature in the reservoir
T_{soil}: Temperature at the ground surface
H: Drilling depth

We then have:

$$T_{res} = 53 \, {}^{\circ}C + \left(0.033 \, \frac{{}^{\circ}C}{m} * 417 \, m\right) = 66.76 \, {}^{\circ}C$$

3.2 CALCULATION OF FLUID DENSITY AS A FUNCTION OF TEMPERATURE

Temperature affects the properties of fluids that influence their flow, mainly their density and viscosity. Since this work deals with basic geothermal energy (temperatures ranging from 30 to 100°C), Lefebvre R.'s [13] proposal from 2006 was used, which indicates the following correlations for assessing the effect of temperature (T) on the density (ρ) and kinematic viscosity of liquid water (ϑ). Dynamic viscosity is defined as the ratio of the viscosity of a fluid to the square of its density. 2006, which indicates the following correlations to evaluate the effect of temperature (T) on the density (ρ) and kinematic viscosity of liquid water (ϑ). Dynamic viscosity (μ) was calculated from the product of density and kinematic viscosity.

$$\rho(T) = 1000.2 - (0.0478 * T) - (3.88 * 10^{-3} * T^2) \tag{16}$$

$$\vartheta(T) = \frac{1.78 * 10^{-6}}{1 + (0.0337 * T) + (0.000221 * T^2)} \tag{17}$$

Table 2 below shows certain properties of liquid water as a function of temperature:

Table 3. Properties of saturated liquid water [14].

T (°C)	$\rho(Kg/m^3)$	$C_p(J/Kg * °C)$	$\lambda(Wm * °C)$	$10^4 * \mu \, (Pa * s)$
0	1002	4218	0.552	17.90
20	1001	4182	0.597	10.10
40	995	4178	0.628	6.55
60	985	4184	0.651	4.71
80	974	4196	0.668	3.55

3.3 CALCULATION OF PRESSURE IN THE RESERVOIR AND AT THE WELLHEAD

The pressure in the reservoir and at the top of the well were not available in the data obtained from the Benin Water Authority. The pressure in the reservoir is estimated based on the depth of the well, taking into account the variation in pressure in geothermal wells [15].

$$\frac{\Delta p}{\Delta Z} = 0.14 \; bar/m \tag{19}$$

$$p_{res} = \frac{\Delta p}{\Delta Z} * H \qquad (20)$$

We obtain:

With p_{res}: Static pressure in the reservoir

$$p_{res} = 0.14 \frac{bar}{m} * 417m = 58.38 \; bars$$

$$p_{res} = 58.38 \; bars$$

To estimate the pressure at the wellhead, the following relationship was used [16]:

$$p_{res} = p_{head} + \rho_w * g * H + \frac{\mu * Q}{e_{res} * k_{in}} + 0{,}06642 * \rho_w * \frac{H}{D^{4,8}} * Q^{1,8} * \vartheta^{0,2} \qquad (21)$$

$$p_{head} = p_{res} - \left(\rho_w * g * H + \frac{\mu * Q}{e_{res} * k_{int}} + 0{,}06642 * \rho_w * \frac{H}{D^{4,8}} * Q^{1,8} * \vartheta^{0,2} \right) \qquad (22)$$

And:

$$k_{int} = \frac{\mu * K}{\rho * g}$$

With:

p_{head}: Pressure at the wellhead
ρ_w: Density of the fluid
Q: Production rate
e_{res}: Thickness of the reservoir
k_{int}: Intrinsic permeability of the fluid
K: Permeability of the fluid
D: Diameter of the wellbore
g: Acceleration due to gravity

Using formula (16), we have ρ_w:

$$\rho_w = \rho(T = 66{,}67) = 1000.2 - 0.0478 * 66{,}67 - 3.88 * 10^{-3} * 66{,}67^2 = 979{,}767 \frac{Kg}{m^3}$$

Formula (17) can be used to calculate the value of ϑ:

$$\vartheta(T = 66.67) = \frac{1.78 * 10^{-6}}{1 + 0.0337 * 66.67 + 0.000221 * 66.67^2} = 4.209 * 10^{-7}$$

The intrinsic permeability value k_{int} is calculated as follows:

$$k_{int} = \frac{4{,}12 * 10^{-4} * 10^{-5}}{979{,}767 * 9{,}81} = 2{,}5719 * 10^{-12} \; m^2$$

Finally, according to formula (22), we have:

$$p_{head} = 15.62 \; bars$$

3.4 RESULTS OBTAINED BY THE CODE DEVELOPED DURING THIS WORK

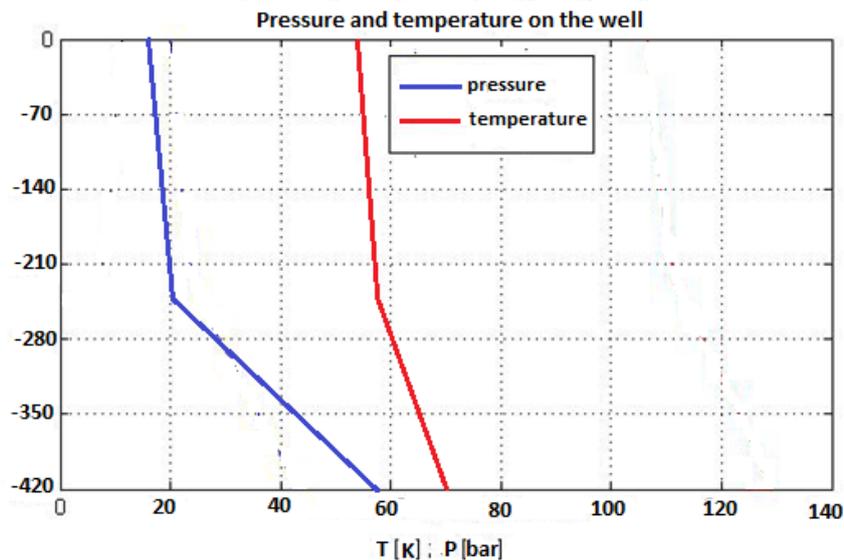Figure 6 below shows the pressure and temperature profiles.

Fig. 6. *Variation in fluid pressure and temperature in the Hêtin-Sota artesian and thermal borehole in the municipality of Dangbo.*

4   DISCUSSION

The results generated by the code developed during this work confirm the temperature values (T_{res}=66.76°C), static pressure (p_{res}=58.38 bars) in the reservoir at this location, and the head pressure (p_{head}=15.62 bars) of the thermal artesian well determined by the analytical method. The pressure profiles (Figure 7) below were extracted from the article "Numerical modeling of flow processes inside geothermal wells: An approach for predicting production characteristics with uncertainties" by O. García-Valladares, P. Sanchez-Upton, and E. Santoyo [16].
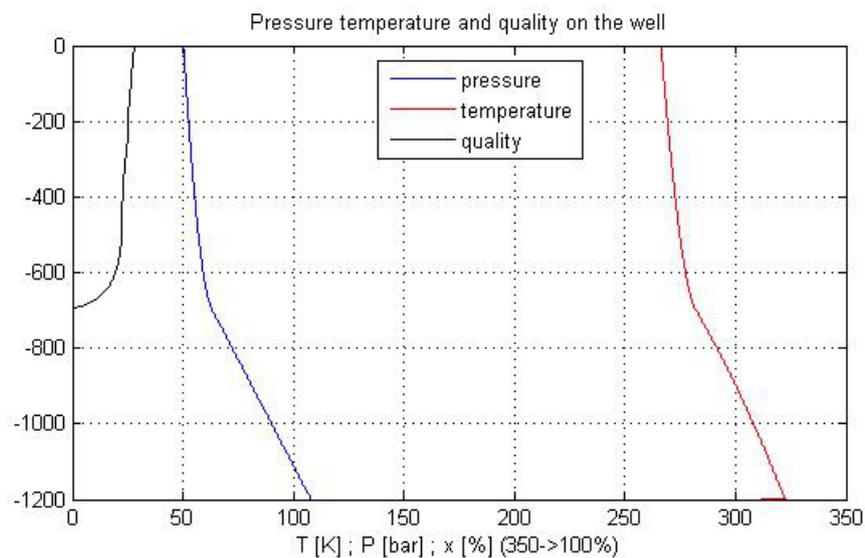

Fig. 7. *Variation in pressure, temperature, and fluid quality in artesian and thermal wells [17].*

It can be seen that the pressure and temperature profiles obtained and those found in the literature are similar.

Geothermal energy is a powerful and sustainable resource that lies beneath our feet and offers a reliable alternative for heating, air conditioning, and electricity generation [18].

According to the French Association of Geothermal Professionals [19], the temperature above ground, i.e., at the top of the artesian and thermal well in Hêtin-Sota in the municipality of Dangbo, is 53°C, therefore between 30°C and 100°C, and the

depth of the well is 417 m, therefore between 400 and 2000 m, the geothermal energy from this well can be harnessed in various ways:

- Through an urban heating network (including collective housing, public buildings such as schools, hospitals, theaters, etc.),
- Through other applications:

  o industrial (processes using steam, hot air, or hot water),
  o agricultural (greenhouse heating, fish farming, drying),
  o water-based (swimming pools, water parks, thermal baths, etc.).

The town of Hêtin-Sota, in the municipality of Dangbo, is part of the Ouémé Valley in Benin, ranked as the second richest valley in the world after the Nile in Egypt [20]. It is undoubtedly a very fertile valley with significant agricultural potential covering more than 70,000 ha, but less than 30% of this area is currently being farmed. In order to reduce poverty and improve food security in the commune of Dangbo in Benin, the results of this work aim to develop the Hêtin-Sota thermal artesian well, using its geothermal energy to enhance the agricultural land of the commune. This article is intended to be a response to an urgent need of the population for agricultural development in the Ouemé area. This well is an excellent source of renewable heat for agriculture. The resource from the Hêtin-Sota underground reservoir is perfectly suited for heating greenhouses, aquaculture, and agricultural drying.

5 CONCLUSION

The development of the Hêtin-Sota artesian and thermal borehole will be of great benefit to the beneficiary communities, the municipality, and the entire national and regional population. The Hêtin-Sota thermal spring is well known and immediately exploitable, and preliminary studies exist, but they do not provide information on all of its characteristics. This article has therefore identified certain characteristics that are essential for the development of the Hêtin-Sota artesian and thermal borehole. The results generated by the code developed during this work confirm the temperature and static pressure values in the reservoir at this location, as well as the pressure value at the head of the artesian thermal borehole determined by the analytical method. A PPP (public-private partnership) is desirable for the equitable use of this resource for therapeutic and recreational purposes, enabling the creation of profitable spas and national parks equipped with public baths for the population. In the future, research on thermal waters should focus on the cultural and medicinal aspects of these hot, mineral-rich fluids.

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