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Numerical Simulation of the Large-Scale Geothermal Reservoir With Multiple-Borehole-Circulation System

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Keywords

Geothermal energy, HDR, numerical simulation, multiple-borehole system, multi-unit geothermal system

ABSTRACT

Design and development of the large-scale geothermal HDR/HWR reservoirs with the multiple-borehole circulation systems can be one of the effective engineering approaches for producing geothermal energy in big amounts, sufficient for further industrial utilization. The major factor that may affect the productivity of this large-scale geothermal reservoir is a proper geometrical arrangement of the multiple-borehole-circulation-system. The numerical simulator FRACSIM-3D is applied for defining the sufficient reservoir size and the relevant multiple-borehole system configurations. Based on the series of computations the efficient location of the production wells is proposed. Within the proposed well arrangement, the number of production wells can be effectively minimized without reduction of the reservoir total thermal output. Assuming a composite multi-unit structure of the reservoir as a hierarchical system, where the whole reservoir consists of a finite number of unites (each local unit has its symmetrically distributed system of injection and production wells), makes possible to reduce the total number of production wells by 55%. The latter was shown on the basis of the large-scale reservoir model with 9 tetragonal overlapped multi-unit systems. Numerical modeling of the composite reservoir constituted by 9 overlapped multiple-borehole units shows that this type of arrangement is more efficient comparing with 9 independent (non-overlapped) units. The flow rate from the production wells located in the overlapped regions of the multi-unit reservoir is higher than in the wells placed within the non-overlapped regions. Since during the stimulation stage the overlapped areas of the multi-unit reservoir are affected by several injection wells, they have higher fracture density than non-overlapped areas. For the multi-unit reservoir system, the total thermal output is almost proportional to the number of the reservoir units. Numerical simulations for the different multi-unit well configurations show that creation of large-scale geothermal reservoirs with effectively arranged multiple-borehole systems is a quite feasible method to enhance thermal performance of the reservoir.

Introduction

Feasibility of producing thermal energy by engineering the of hot dry rock (HDR) and/or hot wet rock (HWR) geothermal systems has been proved through the field-scale hydraulic injection experiments conducted in several countries. Unfortunately, thermal output achieved at the existing HDR/HWR geothermal fields is still insufficient for commercial utilization of HDR/HWR geothermal power stations. For instance, at the Soultz site thermal output was around 10MW (Baumgartner et al., 1998). Hence, assuming thermal output to be proportional to the reservoir volume and taking in account that amount of thermal energy of commercial interest has to be around 100MW, we obtain the required size of the engineered geothermal system to 10 times bigger than Soultz site. In other words, one of the possible approaches for obtaining the higher thermal output could be in increasing the number of production and injection wells and creating a system of several independent engineered reservoirs whose total thermal output is sufficient for commercial applications. However, since the drilling cost is very high, construction of new independent reservoirs and simply mechanically uniting them into a group, which will constitute the power plant, might be not the most efficient method of enhancing the geothermal system productivity. The multiple-borehole system approach (Christopher et al., 1987) with specific (optimal) arrangement of the multi-unit system of production and injection wells is the alternative method for enhancing the engineered geothermal system productivity. Figure 1, overleaf, shows the possible geometrical borehole arrangements for the multi-unit multiple-borehole systems. The fractured unit-reservoirs (shown by the shadowed circles in Figure 1) are combined in groups that constitute the whole reservoir in such a way that the neighboring stimulated regions admit overlapping. The latter, as it will be shown below, is beneficial for the geothermal system perfor-

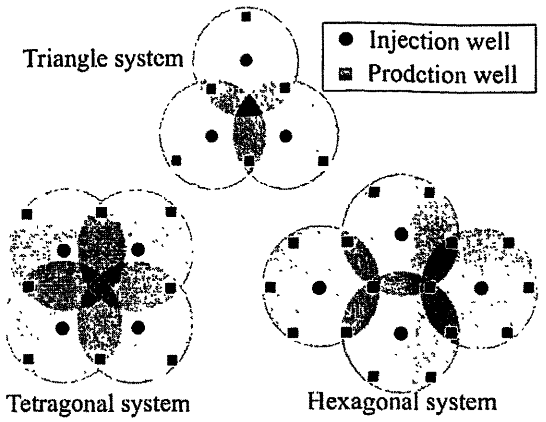

Figure 1. Wells arrangements within the multiple-borehole system.

mance. The objective of the present study is to analyze reservoirs performances for different arrangements of the multiple-borehole systems and to predict dimensions of the HDR/HWR systems sufficient for their commercial utilization.

Table 1. Wells arrangements of injection and production wells for each considered case presented in Figures 1-4.

	Number of wells	
	Injection	Production
Triangle system	3	6
Tetragonal system	4	9
Hexagonal system	6	16

Table 2. Model parameters used in FRACSIM-3D.

Parameter	Value
Fractal dimension of fracture radius	2.0
Fracture density, m^2m^{-3}	1.0
Fracture orientation (dip, azimuth)	Random
Vertical stress at center of model volume, MPa	53.0
Maximum horizontal stress at center of volume, MPa	24.5
Minimum horizontal stress at center of volume, MPa	24.5
Young's modulus of rock, GPa	60
Rock Poisson's ratio	0.25
Rock density, kg m^{-3}	2700
Rock thermal conductivity, W m^{-1} K^{-1}	3.1
Fracture basic friction angle	40°
Shear dilation angle	18°
90% closure stress, MPa	65
In situ permeability, m^2	10^{-15}
Fluid density, kg m^{-3}	1000
Fluid viscosity, N s m^{-2}	3×10^{-4}
Injection fluid temperature, °C	50
Injection flow rate for each well, kg	20
In situ rock temperature at center of model volume, °C	220
Temperature gradient, °C km^{-1}	28
Smallest fracture radius, m	10.5
Largest fracture radius, m	100

Assessment of the Well Arrangement

Influence of the borehole geometrical arrangement on the hydrodynamic and thermal performances of the multi-unit large-scale geothermal reservoir is analyzed with FRACSIM-3Dnumerical simulator (Jing et al., 2000, Shimizu et al., 2000).

The conventional HDR/HWR geothermal reservoir has one injection well (which is used during the reservoir stimulation stage for hydraulic rock-fracturing and during the production stage for injecting the cold water that should be heated within the reservoir) placed in the reservoir center and several production wells located in periphery of the reservoir. In this study we consider the large-scale multi-unit geothermal system, where the single unit will duplicate the well arrangement typical for the conventional HDR reservoir. Namely, each unit consists of one injection or fracturing well and a number of production wells located symmetrically at the same distance from the injection well. Numerical computations are conducted for the multi-unit system whose units may have 3, 4 and 5 production wells (triangle, tetragonal and hexagonal units) and possible overlapping of the stimulated areas of the neighboring unites is assumed. Different overlapping geometries for 3 and 4 unit models are shown in Figure 1. In this figure, small circles and squares denote injection and production wells, respectively. Also well arrangements of injection and production wells for each case are presented in Table 1. In the overlapping multi-unit multiple-borehole systems the number of the production wells can be considerably lower in comparison with the reservoir composed of the same number but independent and non-overlapped units. In numerical computations for different borehole arrangements (see Figure 1) it is assumed that dimension of the model volume, within which the much smaller stimulated region is developed, is 1000^3 m^3. The model volume is centered at a depth of 2000m. The distance between the injection and production wells within each unit is 200m. The vertical and horizontal stresses at the center of the model are 53MPa and 24MPa respectively. Initial rock temperature of reservoir is 220°C. The flow rate in the injection well during production stage is 20kg/sec. The fracture orientation and penny-type fracture center distributions are random.

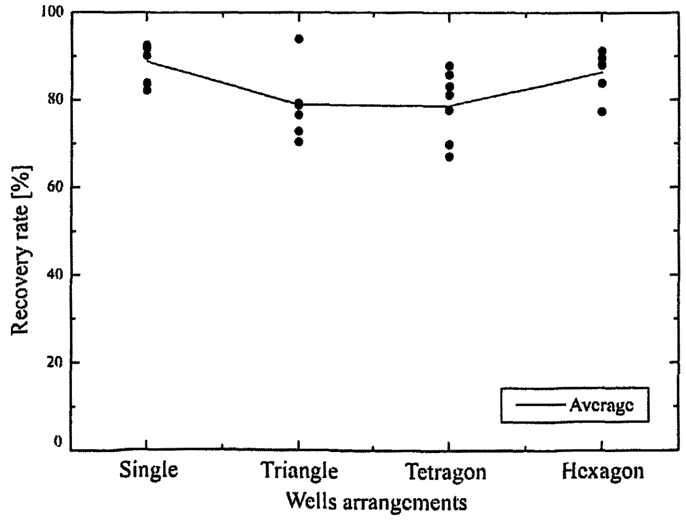

Figure 2. Recovery rate for different wells arrangements.

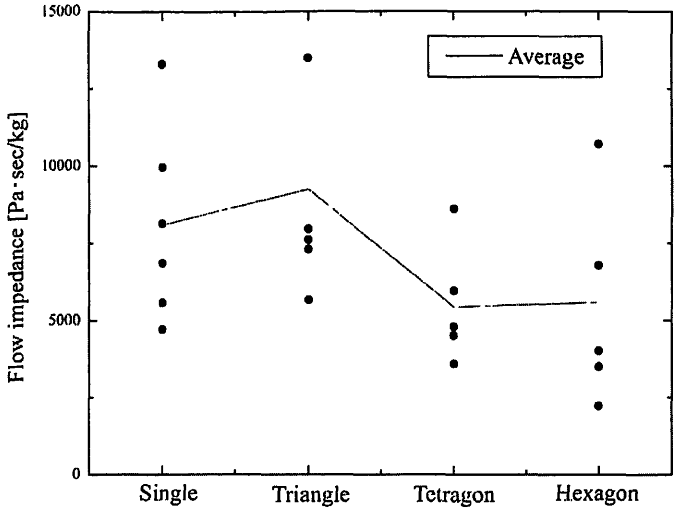

Figure 3. Flow impedance for different wells arrangements.

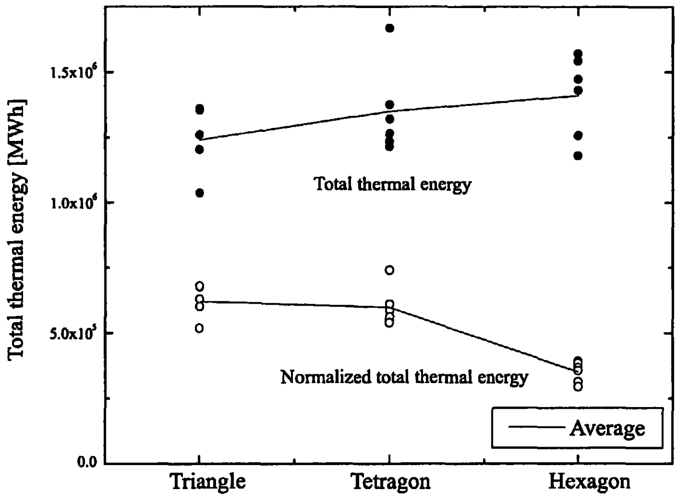

Figure 4. Total recoverable thermal energy for the different wells arrangements.

Other simulation parameters are presented in Table 2. Since the reservoir performance depends on the initial fracture network geometry, 6 different types of fracture networks are generated in numerical experiments. The results are presented in Figures 2, 3 and 4. In these figures, circles denote the results for different geometries of the fracture networks. As can be seen, the recovery rates illustrated in Figure 2 for different well arrangements within multiple-borehole systems are rather high for all arrangement. The flow impedance for the whole multiple-borehole system can be defined as a ratio

$$I = (\overline{P_{in}} - \overline{P_p}) / \sum_{j=1}^{N_p} Q_j^p \qquad (1)$$

where N_p is a number of production wells; $\overline{P_{in}}$ and $\overline{P_P}$ are the mean injection and production pressures, respectively; Q_j^P is a flow rate in the j^{th} production well. The values of the flow impedance of the multiple-borehole system with different borehole arrangements and 6 different fracture network geometries are presented in Figure 3. The average impedances for different borehole arrangements are connected by the solid line. The mean impedances for the tetragon and hexagon borehole arrangements are lower than for the triangle arrangement and for the single-unit system. The values of the total thermal energy normalized by a number of units recovered from the rock during 15 years of multi-unit system exploitation are presented on the upper part of Figure 4. The same data, but additionally divided by the number of production well within the system, is on the lower part of this figure. The noticeable higher values of thermal energy for the systems with bigger number of production wells (hexagon-type) can be readily observed. At the same time, the hexagon-type system shows the lower values of the normalized total thermal energy in comparison with other arrangements.

Assessment of the Large-Scale Multiple-Borehole System Performance

As mentioned, the total thermal output of the HDR power station of commercial interest should be above 100MW. These amounts of thermal energy can be obtained only in the case of a large-scale reservoir. The effect of the borehole arrangement on performance of the multiple-borehole large-scale system is analyzed with FRACSIM-3D simulator. The large-scale multiple-borehole system is investigated on the basis of the tetragonal arrangement, which requires a relatively small number of production wells, and, therefore, its construction can reduce the drilling cost. A schematic sketch of the borehole arrangement for the large-scale tetragonal multiple-borehole system composed of 9 units (which can satisfy the requirements imposed to the thermal output) is presented in Figure 5. For this type of large-scale multiple-borehole systems the number of production wells

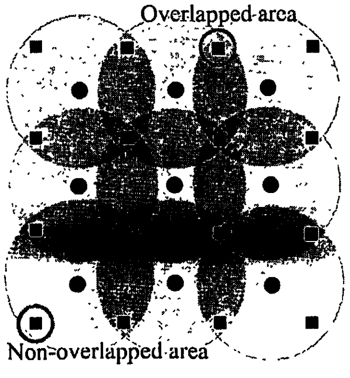

Figure 5. Wells arrangement within the large-scale multiple borehole system.

Table 3. Wells arrangements of Injection and Production wells for each considered case presented in Figures 5-11.

Number of Units	Number of Wells	
	Injection	Production
1	1	4
4	4	9
9	9	16

can be 55% less than the number of the boreholes in the case of system with non-overlapped units. As can be seen, the tetragonal 9-unit system has 9 injection wells and 16 production wells. This 9-units system will be compared with the tetragonal 4-unit and single-unit systems characterized in Table 3. Since results depend on the initial geometry of the fracture network within the reservoir, 7 types of initial fracture network configurations are generated in numerical simulations. The recovery rates for the multi-borehole system and single-unit system are illustrated in Figure 6. As can be seen, increasing the number of units and, consequently, reducing the relative number of production wells for overlapped system (relative to the system with 9 independent units), the recovery rate is always high and practically remains the same as in the case of a single-unit system. Computations of the flow impedances for the multiple-borehole and single-unit systems versus number of units, presented in Figure 7, demonstrate that the large-scale multiple-borehole systems have lower flow impedances than the small-scale multiple-borehole or single-unit systems. The series of computations for different fracture network geometries reveals that the flow impedance in the large-scale multiple-borehole system practically does not depend on the fracture networks configurations.

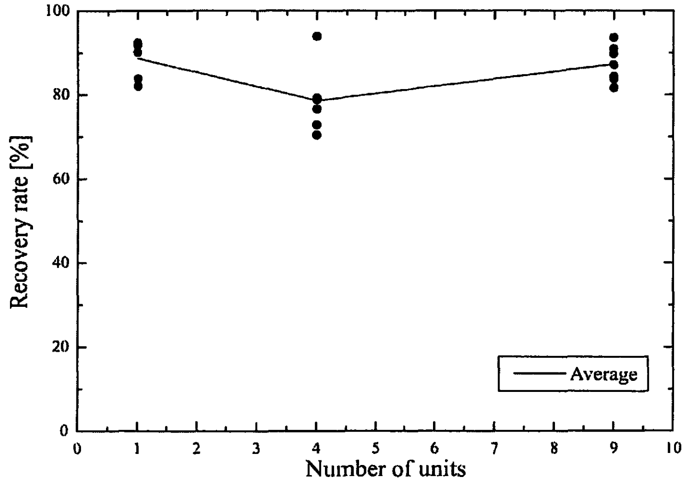

Figure 6. Recovery rate for the large-Scale multiple borehole system.

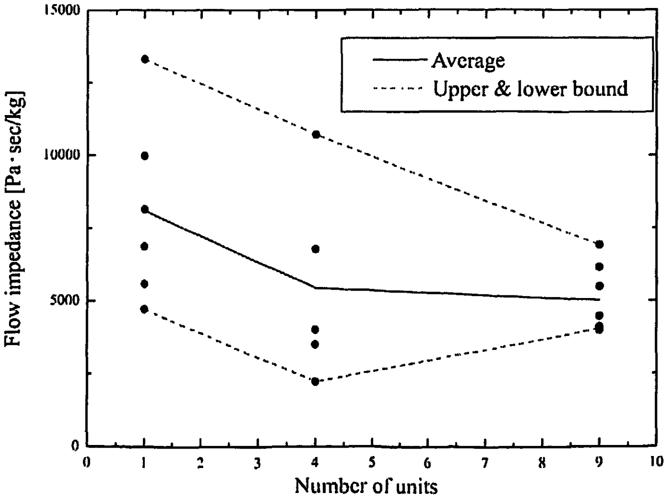

Figure 7. Flow impedance for the large-scale multiple borehole system.

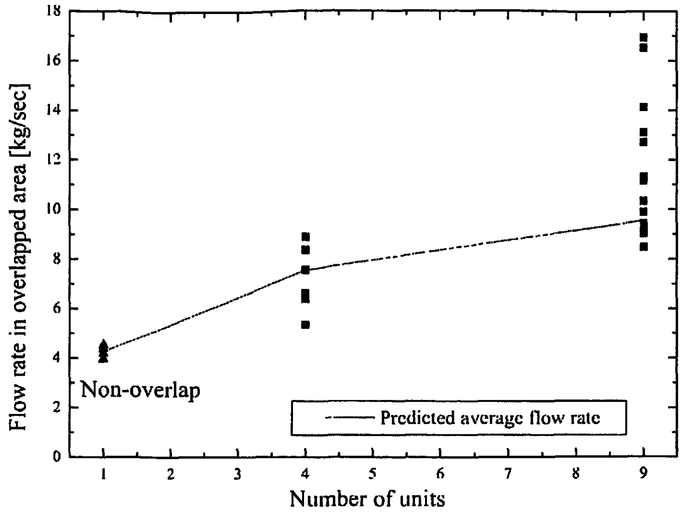

Figure 8. Flow rate in overlapped area of the multiple borehole system.

For the small-scale multiple-borehole system the risk of obtaining the well of low productivity is higher due to possible low permeability of the rock in the vicinity of the production wells. Thus, creating the large-scale multiple-borehole system with overlapped units reduces the possible number of poorly performing production wells and also, as follows from the results of computations, decreases the flow impedance of the reservoir. For different numbers of units within the geothermal system the average flow rate in the production wells located within the overlapped unit areas is illustrated in Figure 8. Although there is no overlapping for the single-unit systems, the results for this case are presented here for comparison with the multiple-borehole systems. The solid line in Figure 8 connects the average flow rate normalized by the number of production wells computed by the formula

$$\sum_{j=1}^{N_p} Q_j^p / N_p .$$

Flow rates from the production wells in the overlapped unit area for the large-scale multiple-borehole system is higher for the multiple-borehole systems with bigger number of units. The

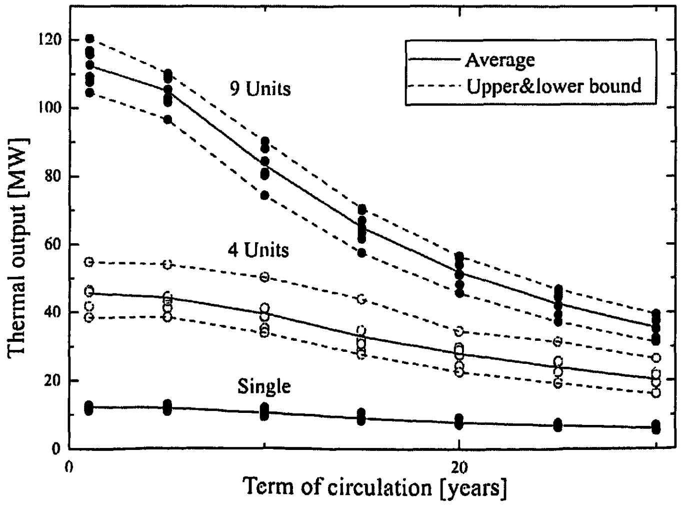

Figure 9. Thermal output with time for the large-scale multiple borehole system.

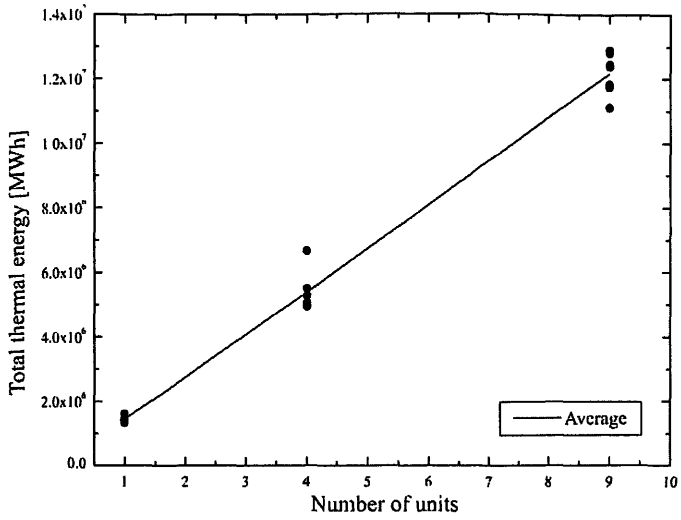

Figure 10. Total thermal energy for the large-scale multiple borehole system.

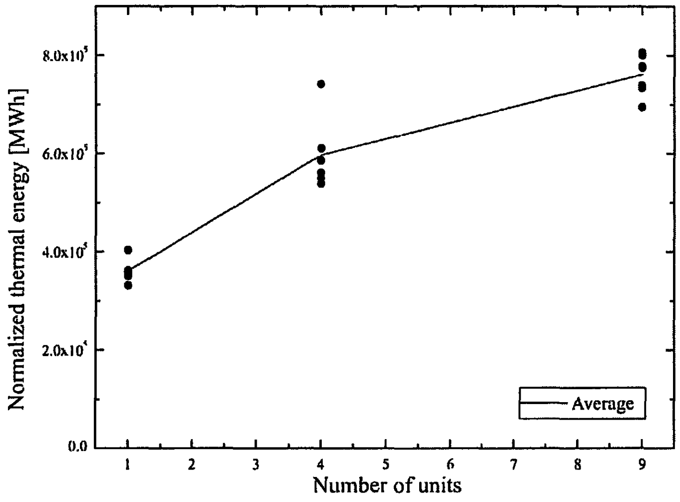

Figure 11. Normalized total recoverable thermal energy for the multiple borehole system.

large-scale multiple-borehole system can reduce the effect of water loss which normally takes place at the edge of fractured area. Since the computed values of flow rate are higher for the overlapped unit areas, the overlapped regions have more developed fracture network and hence higher permeability than other fractured media. The large-scale multiple-borehole system has a larger overlapped unit area. Therefore, creation of the large-scale multiple-borehole systems with overlapped units results in higher conductivity of the fracture network and, hence, in better performance of the geothermal reservoir in total. Variation of the thermal output with time for the large-scale multiple-borehole system is illustrated in Figure 9. Thermal output, which can reach the highest values during the first year of reservoir exploitation (around 110MW), continuously decreases with time. Figure 10 illustrates the total amount of thermal energy recoverable from the multi-unit geothermal system within 15 years of its exploitation. As can be seen, the amount of recoverable thermal energy is proportional to the number of units. The noticeable growth of the total thermal energy recoverable over 15 years of exploitation normalized by the number of production wells is illustrated in Figure 11. Since the drilling cost in engineered geothermal systems is very high, the number of the wells should be minimized (preferably, without loss of reservoir productivity). The large-scale multiple-borehole systems with overlapped units can simultaneously guarantee the high thermal output and allow the substantial reduction of the number of production wells (relative to the analogues system with independent units).

Conclusions

In the present work, the FRACSIM-3D numerical simulator was used to assess the hydraulic and thermal performances of the multiple-borehole HDR/HWR geothermal systems with respect to their possible commercial utilization. Comparative analysis of the reservoirs with different borehole arrangements reveals that the tetragon-type arrangement of the multi-unit system is beneficial in sense of reducing the number of production wells. Implementation of the large-scale multiple-borehole system with 9 overlapped tetragonal-type units can provide the 55% reduction in a number of production wells comparing with the system with the same number of non-overlapped independent units. While the ratio of the number of production wells to the number of overlapped units is getting smaller for the large-scale multi-unit system, this system can provide almost the same flow rate as a single-unit system. This is because the flow impedance of the large-scale multiple-borehole system decreases with increasing the number of units. The production wells located in the overlapped unit area can provide higher flow rates. The total thermal output linearly increases with increasing the number of units. The high values of the total thermal energy than other, which are computed in the case of large-scale multiple-borehole system with overlapped unit areas, demonstrate the advantages of these systems in sense of their good thermal performance and feasibility to reduce a number of production wells.

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