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Potential application of vacuum insulated tubing for deep borehole heat exchangers

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ABSTRACT

During recent Paris climate agreement, 195 courtiers pledged to reduce the greenhouse gas emissions and pursue effects to limit the global temperature increase to 2 °C. Geothermal resources, as renewable sources of energy, can contribute to electricity, as well as heat production without having any negative impacts on environment or the security of energy supply. One of the ways to extract geothermal heat from the Earth's crust are Deep Borehole Heat Exchangers, which can be either drilled especially for such purposes or, what is more cost effective, reconstructed from already existing, negative or abandoned oil or natural gas wells. In many depleted boreholes, exploiting underground geothermal waters is impossible or technically complex, therefore potential reconstruction for heat exchanger might be the only possible solution that allows utilizing geothermal heat.

Polish energy sector is heavily dependent on coal resulting in large CO_2 emission per capita. The country has considerable potential for geothermal energy development, as there are large numbers of deep and abandoned wells that might be utilized for geothermal heat production. Following paper investigates potential reconstruction of abandoned or negative wells into deep coaxial borehole heat exchangers. Main focus was put on selection of coaxial inner column which enables for heat carrier circulation. To maximize the heat uptake from geothermal systems based on borehole heat exchangers, it is advised to use inner column made from material with lowest possible thermal conductivity coefficient. Vacuum Insulated Tubing, as one of the options of insulated inner column, can significantly improve heat production and increase efficient energy use. This technology found plethora of applications in offshore and onshore petroleum industry and is yet to gain more popularity within geothermal sector.

1. Introduction

Geothermal systems based on Borehole Heat Exchangers (BHE) are being increasingly utilised for managing heat distribution in public and industrial housing (Rosen and Dincer, 2011). The main advantage of BHE's is a potential use as an Underground Thermal Energy Storage (UTES), providing seasonal storage of heat. UTES is subject of many current research studies (Kizilkan and Dincer, 2015; Kurevija et al., 2012; Li et al., 2014; Śliwa and Rosen, 2015).

The main parameter affecting the efficiency of BHE systems is characteristic of underground rock mass, which includes lithology and hydrodynamic conditions. Formation parameters, such as these presented in list below, cannot be regulated or changed during drilling or geothermal heat production (Śliwa and Kotyza, 2000; Śliwa and Rosen, 2017):

a) geothermal gradient,
b) natural heat flux,
c) thermal conductivity, specific heat, diffusivity and density of rock mass,
d) anisotropy of thermal conductivity of rock mass,
e) porosity, saturation and hydrodynamic characteristics of rock mass,
f) type of reservoir fluids,
g) natural velocity and filtration direction.

The efficiency and amount of heat reaching the earth's surface due to closed-loop carrier circulation in BHE system depends largely on well construction design which includes equipment already installed for its primary purpose (i.e. casing and cement) and equipment needed for reconstruction and heat extraction (e.g. coaxial inner column and cement plug). BHE can be applied in vertical or directional wells (Knez, 2014; Quosay and Knez, 2016). Typical construction designs of BHE

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system include:

a) single and multi (e.g. double) U-pipe,
b) coaxial inner column (Śliwa and Rosen, 2015),
c) helical BHE (Zarrella and De Carli, 2013; Zarrella et al., 2013; Zarrella and De Carli, 2013),
d) BHE in piles (Li and Lai, 2012),
e) BHE with direct underground evaporation of heat carrier.

BHE system can be reconstructed from abandoned wells, which were originally utilised for natural gas or oil extraction (Cheng et al., 2013; Davis and Michaelides, 2009; Sapińska-Śliwa et al., 2015; Sapińska-Śliwa et al., 2016). Major construction and design characteristics required for potential reconstruction of already existing wells into BHE include (Śliwa and Kotyza, 2000):

a) well diameter, inclination and azimuth,
b) depth of packer and/or cement plug in a negative and/or abandoned well,
c) number, length and diameter of casing strings,
d) internal and external diameter and length of coaxial inner column,
e) quality and condition of material used for inner column insulation,
f) heat resistance of coaxial inner column material,
g) centricity of coaxial inner column,
h) distance between multiple BHE's.

Geological and construction design parameters described above influence heat production efficiency from BHE. Operating parameters of BHE systems include following parameters (Śliwa and Kotyza, 2000):

a) mean annual heat production,
b) heating power,
c) temperature, flow rate, flow reststance and type of heat carrier,
d) rock mass temperature restoration,
e) operation time,
f) distance between heat recipient and BHE system,
g) type of heat consumer, heat rate and heat consumption,
h) local climate,
i) cost of other available heat sources.

BHE's technology allows heat exchange between rock formation and heat carrier, circulating in closed-loop system between surface and underground reservoir. Borehole Thermal Energy Storage (BTES) is an underground system consisting of group of single BHE's. This arrangement can supply heat directly, for instance in deeper wells, or indirectly i.e. with heat pumps, especially when harvesting low-enthalpy geothermal resources at shallower depths (Jaszczur et al., 2017).

Deep Borehole Heat Exchangers (DBHE) can work only as a heat source. Such systems are expensive, especially drilling and completion costs, and involves finding a consumer in short distance from the borehole, as heat losses are significant (Sapińska-Śliwa et al., 2015). During reconstruction, of already existing, abandoned or negative wells for DBHE's, inner column is the most important feature, which determines overall success. The application of insulated inner pipe with lowest possible thermal conductivity coefficient can reduce drastically heat losses of circulating heat carrier. As a result, insulated pipe will increase the heat uptake (Śliwa and Rosen, 2015). Well reconstruction for DBHE includes partial abandonment, which constitutes of removing heavy mud from the borehole, sealing off perforated intervals using cement plugs and installing inner, insulated column in leaktight, closed-loop system. Drilling a borehole especially for DBHE purposes is proven to be not profitable (Śliwa et al., 2016).

Multi-layered insulated pipe that allowed for steam injection into oil reservoirs for enhanced recovery and production increase was first introduced in 1970 by General Electric. This new technology enabled to increase efficiency of steam injections and significantly decrease operational costs. Further development allowed increasing insulation by introducing gas (e.g. argon) into the annular. In 1983 Babcock & Wilcox company launched double-layered Vacuum Insulated Tubing (VIT) with thermal conductivity ranged from 0.003 to 0.004 W/(m K) (Ayres et al., 1985). CoconoPhillips claimed that VIT is one of the key technologies for cost reduction of the oil sand supply (ConocoPhillips, 2014). However, implementation of this new technique has been rough in regards to difficulties in assessing its energy efficiency, environmental and economic values. In addition, projected lifetime of VIT predicted by some researchers is reported to be seven years in theory and only one year in reality (Zhou et al., 2015). As a result, VIT needs a number of computational and experimental improvements (Gosch et al., 2004). VIT technology drastically decreases heat transfer between inner coaxial column and casing strings. Such tubes are implemented to eliminate heat exchange caused by convection, radiation and conduction. These features can lengthen the life expectancy of the DBHE systems, increase efficiency and decrease costs without any negative impact on environment. Maximum bottom hole temperature for VIT application is reported to be 350 °C and maximum depth is 3600 m. Vacuum pipes can be exercised in slimholes (holes with diameter 6" or less) however heat path and thus overall efficiency will be decreased significantly. As for manufacturer brochures, heat carrier in VIT loses around 12 °C on 1542 m length of pipe. In situation where conventional steel pipes are utilised, heat loss is however around 8 times higher (Helix Oilfield Services Ltd., 2017). This phenomenon can be seen in Fig. 1. Vacuum tubes can demonstrate thermal conductivity coefficient varied from 0.006 to 0.0008 W/(m·K), whereas for conventional steel pipes it amounts to around 40 W/(m K) (Fig. 1). As thermal conductivity coefficient for VIT can be only represented in particular range, manufacturers implemented insulating grades represented by letter (e.g. B, C, E).

Fig. 1 illustrates temperature profiles of 3000 m DBHE. Circulation of closed-loop system in DBHE is executed by pumping heat carrier into the annular and carried through inner column to the surface. There are four different variants of insulating grades with different inner column construction. The lowest value of 0.01 W/(m K) represents thermal conductivity coefficient of VIT (1), 0.12 W/(m K) indicates good insulation (2), 1.16 W/(m K) represents average insulation grade (3) and 46.1 W/(m K) indicates no insulation (steel column with no insulation material) (4) (Morita and Tago 1995).

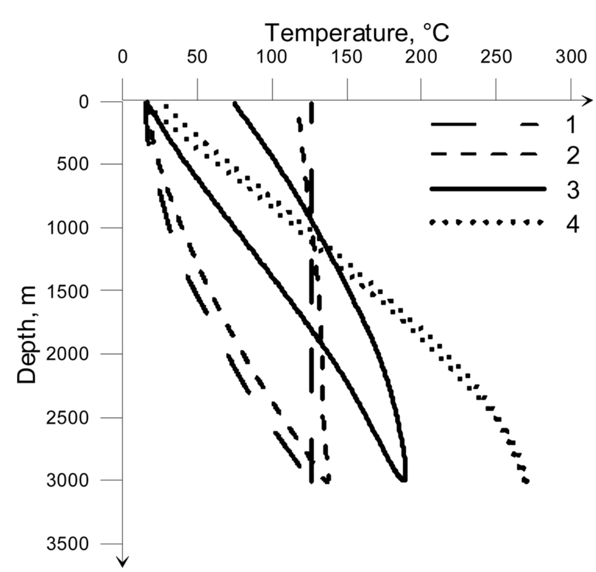

Fig. 1. Temperature profiles in coaxial DBHE of 3000 m depth for different values of thermal conductivity coefficients of inner column (1–0.01 $Wm^{-1}K^{-1}$, 2–0.12 $Wm^{-1}K^{-1}$, 3–1.16 $Wm^{-1}K^{-1}$, 4–46.1 $Wm^{-1}K^{-1}$).

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