

Convective Heat Transfer Enhancement and Emissions Reduction in Combined Heat and Power Reservoir Systems-New Construction Methodology

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Abstract— Numerical simulation of a geothermal reservoir, modeled as a bottom-heated square box, filled with water-CO₂ mixture is presented in this work. In first part, results for two limited cases of a reservoir filled with either pure water or CO₂ are presented. Effects of different parameters including CO₂ concentration as well as reservoir pressure and temperature on the overall performance of the system are investigated. With a fixed reservoir pressure and temperature, any increase in CO₂ concentration leads to better performance, that is, stronger convection and higher heat transfer rates. With a fixed CO₂ concentration, however, the reservoir pressure and temperature can significantly affect the overall heat transfer and flow rate from the reservoir. The second part calculates amount of CO₂, SO₂, NO and particulate matters emissions from main grid and from μ sources which forms micro grid. The results indicates that more penetration of μ sources in the power systems especially the renewable sources will help in reducing or removing emission problems and solve the green house gas problems. Finally this paper proved with calculations that the micro grid can solve most of the problems which facing the conventional power system and keep the surrounding environment clean from pollution and the micro grid will be the future power system.

Index Terms— Geothermal reservoir, Convective Heat Transfer, Computational fluid dynamics, Micro Grid, Voltage Enhancement and Power Saving, Emission Reduction.

I. INTRODUCTION

Simultaneous power generation and geo sequestration make CO₂ a very attractive choice for geothermal power plants. As such, carbon-dioxide-based engineered geothermal systems (CO₂-EGS) have been previously proposed as an alternative to water-based EGS systems [1]. Additionally, [2] investigated the effects of CO₂-rich phase compositions on the production flow rate and the heat extraction from the reservoir. What is yet to be reported in the literature is a detailed numerical simulation of a water-CO₂ mixture filling a reservoir. Increasing penetration of distributed generation (DG) resources to the low voltage (LV) grids, such as photovoltaics,

CHP micro-turbines, small wind turbines areas and possibly fuel cells, alters the traditional operating principle of the grids [3-5]. A particularly promising aspect, related to the proliferation of small-scale decentralized generations (μ sources), is the possibility for parts of the network comprising sufficient generating resources to operate in isolation from the main grid, in a deliberate and controlled way. These are called micro grids and the study and development of technology to permit their efficient operation has started with a great momentum [6,7].

Enhanced Geothermal Systems, also known as Engineered Geothermal Systems or Hot Dry Rock (HDR) systems, differ from the traditional hydrothermal systems in that the target reservoir typically consists of low permeability and low porosity rock with low fluid content and limited hydraulic connectivity between production and injection wells [8,9]. Hydraulic stimulation is required to enhance the permeability of the reservoir in order to create sufficient connectivity for water or perhaps CO₂ as heat transfer fluid. Proper reservoir management using a “heat farming” strategy can ensure the renewability of the system on societal timescales [10-13]. Convective fluid plumes may play a role in enhancing heat flows from the mantle to geothermal reservoirs and within the reservoirs themselves. Additionally, convection within a geothermal reservoir may enhance the productive life-time of geothermal reservoir systems by enhancing heat supply from underlying strata and by ensuring a more even distribution of thermal energy throughout the reservoir [14-16].

As micro grid is able to supply its loads locally, it reduces the amount of power transfer from remote generation via transmission and distribution circuits. Hence, it will reduce system losses. This also leads to the reduction of total energy produced by central power plants. Thus, it will also reduce Pollutants (CO₂, NO_x, SO₂ and other particulate matter) from these plants.

II. MATERIALS AND METHODS

These findings have implications for the study of natural geothermal reservoirs, where the role of dissolved gas exsolution on heat transfer enhancement remains unquantified. Additionally, these findings may be of potential interest with regard to CO₂ injection into geothermal reservoirs, as it may lead to improved productivity through the mechanisms elucidated in this work. The magnitude of this effect on the thermal productivity of geothermal power plants is difficult at this stage to quantify and probably not meaningful to speculate on due to the limitation of assessing only single-phase flow behaviors within the reservoir.

A. Modeling

The reservoir is modeled as a bottom-heated square box with adiabatic lateral boundaries and a cold top wall as Figure 1 shows. The cold and hot temperatures are varied from 335 to 435 K and 425 to 525 K, respectively, in a way that the hot-cold temperature difference remains at 90 K for each case. The reservoir porosity is fixed at 0.05 and the permeability-length product is kept constant at 10⁻¹¹ m³ similar with no through-flow [17]. The reservoir pressure is varied from 20 to 60 MPa to cover a wide range of practical applications for geothermal development.

B. Numerical Details

Grid independence was verified by running the software on different combination of grid sizes. It was observed that the results changed less than 2% when a 100 × 100 mesh system is used instead of a finer mesh with 200 × 200 grid points. Results are also verified for constant property free convection of water in a porous cavity, that is, the Darcy-Benard problem. It was noted that the correlation between Nusselt number (Nu) and Rayleigh number (Ra) Nu = Ra/40 best fits out numerical data, as Figure 2 shows.

a) Numerical Results

We focus on free convection heat and fluid flow of a water-CO₂ mixture in a porous cavity. So that we use Nu and maximum flow rate as our metrics to evaluate the strength of convective flow patterns. Nu is the total heat transfer divided by that of pure conduction through the same cavity. As such, any Nu value in excess of unity shows some degree of convection. Obviously, higher Nu values mark stronger convective cells.

We systematically change the CO₂ mass fraction from zero (pure water) to unity (pure CO₂) over a range of reservoir pressure and temperature in a way that the hot-cold temperature difference remains the same. For a constant property subcritical fluid flow, one would expect that, with the same temperature difference and, hence, the same Rayleigh number (Ra), the overall heat transfer and fluid flow will not alter. Figure 3 shows Nu versus CO₂ mass fraction at 20 MPa with the same hot-cold temperature difference but with different hot and cold temperatures as denoted on the plots. As seen, the heat transfer increases with CO₂ mass fraction for any given Th and Tc combination. Furthermore, moving from pure

water to pure CO₂, the increase in heat transfer is significant; about one order of magnitude is the minimal heat transfer augmentation. This is obviously in favor of low temperature geothermal reservoirs which may not be productive when pure water is the working fluid.

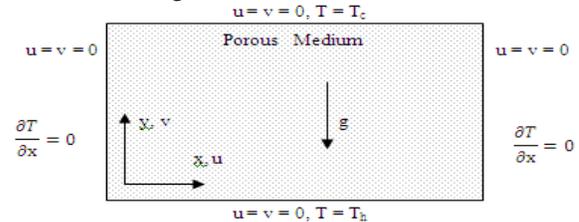


Fig.1 Schematic view of the computational domain

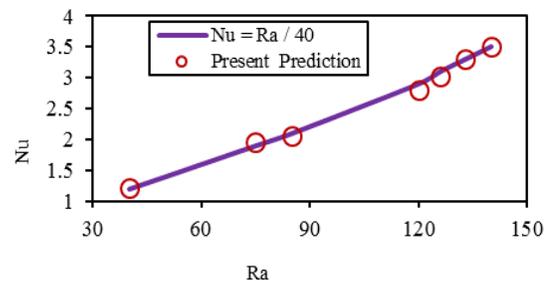


Fig. 2 Validation of present CFD results against existing correlation for pure water

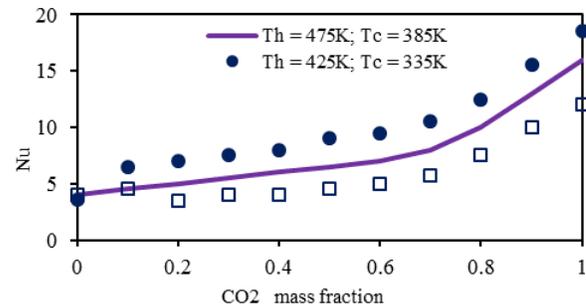


Fig. 3 Nusselt number versus CO₂ mass fraction for different Th and Tc combinations with ΔT = 90K

Figures (1, 2 & 3) are presented to demonstrate Nu versus CO₂ mass fraction for different reservoir pressures and hot cold temperature combinations. Nu increases with mass fraction for a fixed pressure and hot-cold temperature combination. Comparing the relationship between any of Figures (1, 2 & 3) for a fixed pressure will result in conclusions similar to what were drawn based on close examination of Figure 3. That is, heat transfer increases for temperatures close to pseudo critical conditions. Moreover, based on plots in the same chart, increasing the pressure leads to lower heat transfer rates for a fixed CO₂ mass fraction and temperature. As a result, at the same temperature, either of the two fluids will be less buoyant at higher pressures when compared to lower ones, so will be the mixture in the absence of any phase transitions. The convective flow rates also reflect a dependence on compressibility, as demonstrated by Figure 5. The dimensionless flow rate normalized stream function on the vertical axis is obtained by



normalizing the actual flow rate with appropriate scales for velocity, area, and density:

$$\xi = \frac{m}{(\rho u A)} \quad (1)$$

Mathematically, it means that we used the group ρAu to non-dimensionalize the flow rate. It needs to be mentioned that the choice of these parameters is optional but we tried to use constant values for density and length to make it easy for the reader to generate estimates, based on our calculation, for expected flow rates through a given reservoir.

The density of water at atmospheric condition is used where the unit area is used defined as the length of the cavity multiplied by unity (1 m).

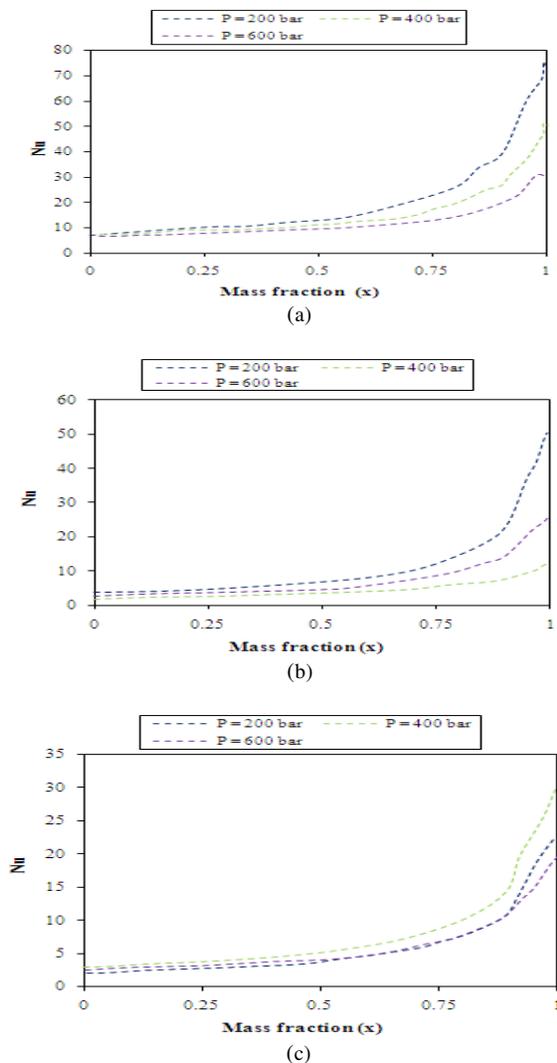


Fig. 4 Nusselt number versus CO₂ mass fraction for different reservoir pressures and temperature combinations : (a) $T_h = 425\text{K}$; $T_c = 335\text{K}$, (b) $T_h = 475\text{K}$; $T_c = 385\text{K}$, and (c) $T_h = 525\text{K}$; $T_c = 435\text{K}$

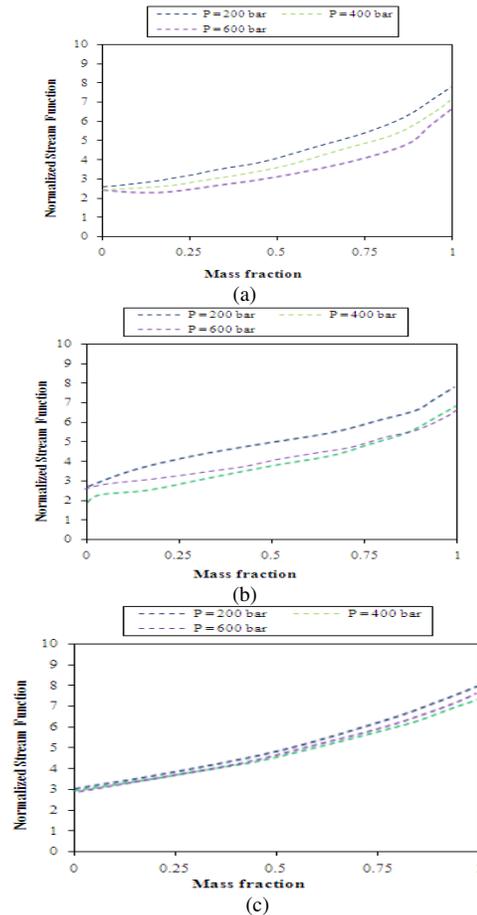


Fig. 5 Dimensionless mass flow rate versus CO₂ mass fraction for different pressures and temperature combinations; (a) $T_h = 425\text{K}$; $T_c = 335\text{K}$, (b) $T_h = 475\text{K}$; $T_c = 385\text{K}$, and (c) $T_h = 525\text{K}$; $T_c = 435\text{K}$

The product of thermal diffusivity and density is independent. This flow rate here is the buoyancy-induced flow rate due to changes in fluid density. The buoyancy-induced flow leads to an upward movement of hot fluid toward the top wall, where it is cooled and then displaced by other rising hot fluid. Results of mass flow rate normalized and presented in Figure 5 for different mass fractions, pressure, and temperature combinations. Similar to Nu plots, one notes that the mass flow rate is sensitive not only to the temperature difference but also to the actual wall temperature values. Furthermore, higher CO₂ mass fraction leads to higher flow rates. It can be noted, moving from Figures (5a, 5b&5c), that flow rates are less sensitive to pressure as T_h is increased. With a fixed T_h and T_c , one notes different trends in flow rate when pressure changes. Depending on the temperature values, an increase in pressure can either increase (Figure 5a) or decrease the flow rate (Figure 5b).

This work is an initial analysis of the role of CO₂ enhancement of convective heat transfer within geothermal reservoirs. It deliberately assesses the behavior of a single phase mixture of the two components. Further work is necessary to extend this to account for multiple phases. There

are three particular qualitative effects through which multiphase flow is expected to alter the results presented here.

- i. Transient ex solution of dissolved CO₂ as bubbles within the two-phase region should lead to local enhancement of convective flow around the bubble due to its upwards buoyancy-driven motion.
- ii. Relative permeability within the two-phase region would act to reduce enhancement of flows, as the reservoir permeability to the minor phase within a two-phase flow is typically substantially reduced.
- iii. Under steady- state conditions, there would be an expectation of phase separation into two horizontal phases based on relative density, that is, an upper CO₂-rich phase and a lower H₂O-rich phase. The upper phase would experience significantly enhanced convective heat transfer rates, as it would have internal heat transfer characteristics similar to the right sides of Figures 4 and 5.

Considering that the results presented here indicate that CO₂ may enhance flow rates by up to a factor of 2.67, we conclude that this is a potentially important mode of heat transport within geothermal reservoirs.

C. Benchmark Network Analysis using Micro Grids

Distributed generation (DG) operation can improve the voltage profile in the micro grid nodes especially at the feeder where μ sources are installed. Therefore the installation of DG sources seems to be a solution in improving the voltage profile within a micro grid during times of low voltages (peak loads).

Bench mark network described in references [20, 21] is used for analysis. Single line diagram with all buses marked

Table 1 Line data for micro grid

Sending Bus	Receiving Bus	R (p.u.)	X (p.u.)
0	1	0.0025	0.01
1	2	0.0001	0.0001
2	3	0.0125	0.00375
3	4	0.0125	0.00375
4	5	0.0125	0.00375
5	6	0.0125	0.00375
3	7	0.021875	0.004375
1	8	0.033125	0.00875
1	9	0.0075	0.005
9	10	0.015	0.010625
10	11	0.02125	0.005625
11	12	0.02125	0.005625
9	13	0.010625	0.005625
13	14	0.010625	0.005625
10	15	0.023125	0.00625
15	16	0.023125	0.00625

Table 2 Data of the used μ sources

Unit ID	Unit Name	Minimum capacity (KW)	Minimum capacity (KW)

1	Micro turbine	2	30
2	Fuel Cell	1	30

is shown at the end of the paper (Figure 17). One feeder network includes 7 buses (buses 1-7) represent the residential loads. Industrial load (bus 8) represents the second feeder. The remaining buses (buses 9-16) feed commercial loads and represent the third feeder. Impedance of the network lines and data for μ sources used are given in Tables 1-2 respectively.

The units have been calculated in power base of 100 KVA and voltage base 400V. Bus 0 represents the main grid distribution network. Micro turbine is located at bus 7, fuel cell is located at bus 6, and PV₃ is located at bus 5 while wind turbine and PV_{2,5} are connected to bus 4.

a. Load Curves

Aggregate daily load curves for single feeder residential loads and three feeders residential, industrial and commercial loads are shown in Figure 6.

b. Voltage Enhancement and Power Saving

Load flow program is used to calculate the voltages at all nodes of the micro grid. Results are shown in Figures (7a, 7b, 8a, 8b, 8c & 8d). The power factor is 0.85 lagging for

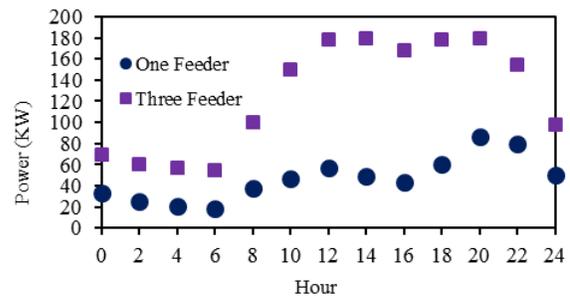
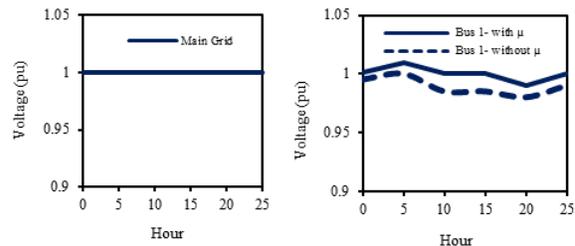


Fig. 6 Daily load curves for one feeder and three feeders Networks



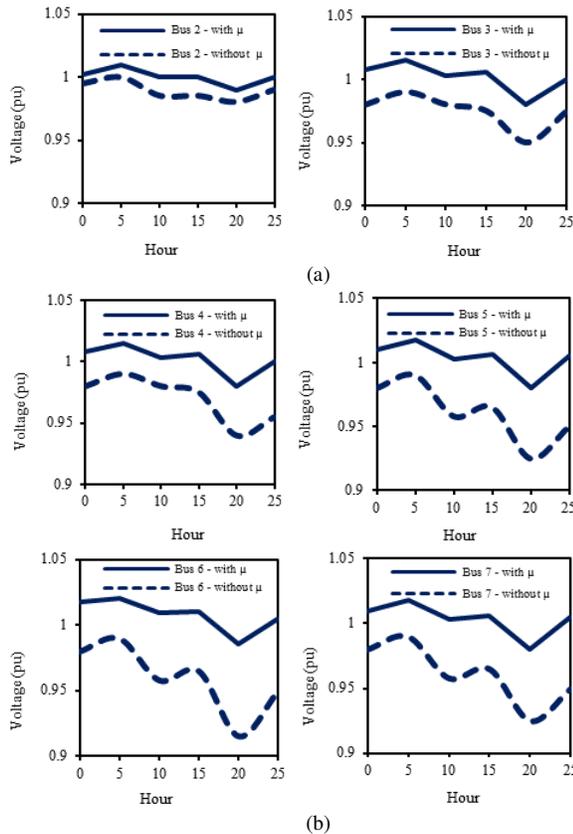


Fig.7 Voltage for single feeder network with and without using μ sources, **a** main grid, buses 1,2 and 3 and **b** buses 4, 5, 6 and 7

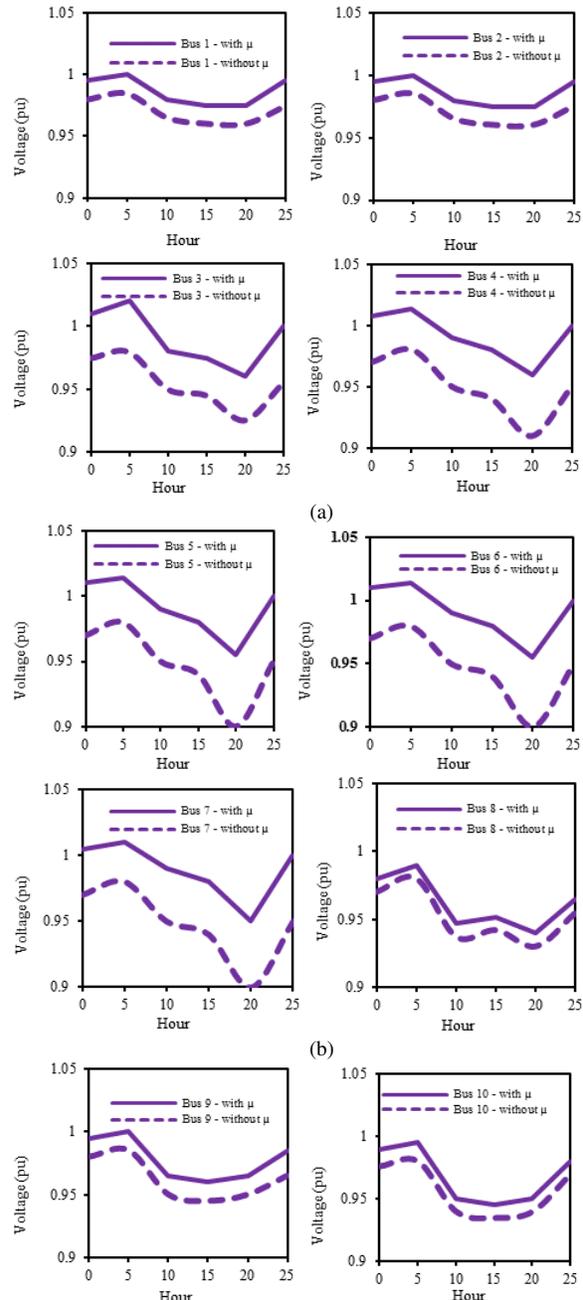
residential and commercial consumers and 0.9 for the industrial ones. All calculations have been made at p.u of base $V_{base} = 400$ V and $S_{base} = 100$ KVA. The network data are presented in Sections 3 and 3.1. It has also been assumed that in the μ sources the power electronic interface has been adjusted to give or absorb zero reactive power at all base buses except fuel cell and micro turbine buses. At all time, we assume that the micro turbine and fuel cell operated at 84% of their maximum capacity (25 KW).

The dashed lines represent results without μ sources while the solid lines represent results With using μ sources. From the above results the following points can be raised:

- i. With using μ sources, in the two studied cases (single feeder and three feeder), the voltages at all buses are improved.
- ii. Amount of improvement in case of single feeder network is better than three feeder case because amount of power produced by the μ sources is less than the power demand by loads of the three feeder, also the μ sources are far from loads of industrial (bus 8) and commercial (buses 9-16) feeders.
- iii. The largest drop of the voltage is about 4.5% without μ

sources, because we assume that the voltage at the main grid (distribution network) equal to 1 p.u., if we assume that the voltage at the distribution network less than 1 p.u (due to voltage drop in the transmission network) as actually occur, the voltage drop without using μ sources will be more than 4% and may be reach to 8%.

The total power losses for one feeder and three feeder networks at the same conditions mentioned before are



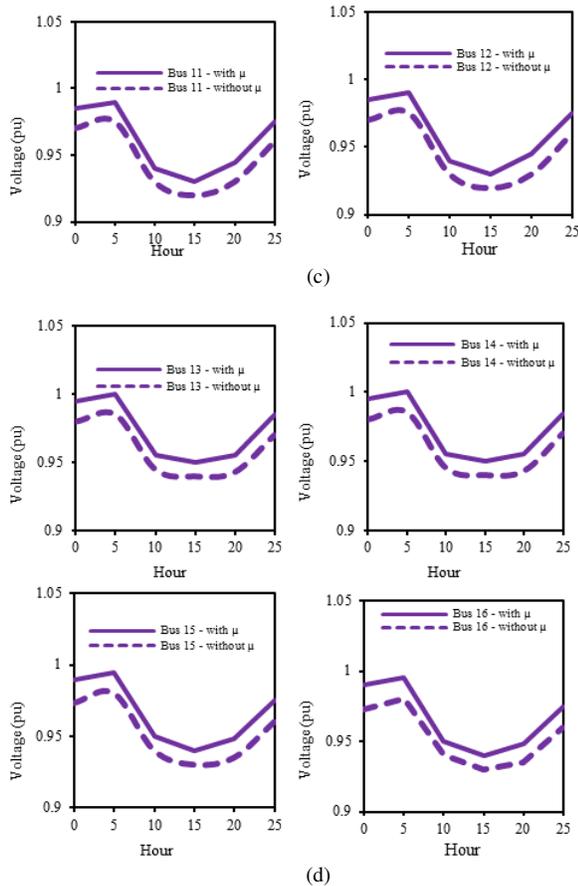


Fig. 8 Voltage for three feeder network with and without using μ sources, **a** buses 1,2,3 and 4, **b** buses 5,6,7 and 8, **c** buses 9,10,11 and 12 and **d** buses 13, 14, 15 and 16

evaluated and the results are shown in Figures (9a&9b).

From the simulation figures, the following points can be summarized:

- i. The total power losses with using μ sources is less than the losses when μ sources are not used, because using μ sources reduces the distance between the load and generation and also, reduce the current flowing from the main grid.
- ii. In addition, in our analysis, we calculated the losses in the transformer which connect the main grid with the micro grid network. If we take the losses in the upper distribution and transmission networks, the amount of losses will exceed the calculated value.
- iii. For single feeder network, at lightly load μ sources production will feeds the load and export the remaining power to the distribution grid which make the losses with using μ sources larger than losses without μ sources.

C. Emission Reduction Evaluation

In order to evaluate the potential of environmental benefits from the micro grids, data about the emissions from the main grid and data about the emissions of the μ sources should be taken into account. The emissions for which calculations are made are: CO_2 , SO_2 , NO and particulate matters.

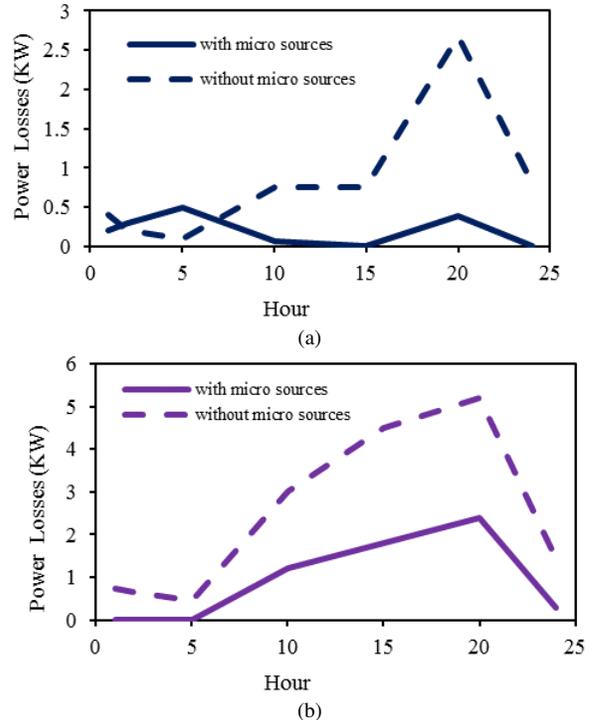


Fig.9 Total losses for with and without μ sources, **a.** single feeder network, **b.** Three feeders network.

Emissions of the Main Grid

The production of the μ sources displaces power from the main grid. Thus the emissions avoided are an average value of the main grid emissions multiplied by the production of the μ sources. In our study, typical values of emissions have been used as shown in Table 3.

Table 3 Typical values of emissions from the main grid

Pollutants	Gr/ KWh
CO_2	889
SO_2	1.8
NO_x	1.6
Particulate Matters	0.501

Impact of μ Sources

From the installed μ sources the ones that consume fuels have emissions which are significantly lower than the ones in the main grid. Whereas the renewable such as wind and solar energies have zero emissions in their operation. It is assumed that the fuel burned by the Micro turbine and the fuel cells is natural gas. Table 4 gives the data used for our analysis.

III. RESULTS AND DISCUSSION

Amounts of emissions with and without using μ sources for single feeder and three feeder networks are shown in Figures 15 and 16. According to the results obtained in the previous figures the following point can be summarized:

Table 4 Typical emission data for μ sources

Unit Name	CO ₂ Coeff. (gr/KWh)	NO _x Coeff. (gr/KWh)	SO ₂ Coeff. (gr/KWh)	Parti. Matters (gr/KWh)
Micro turbine	724.6	0.2	0.004	0.041
Fuel Cell	489	0.01	0.003	0.001

- i. Using μ sources has large effect in reducing the amount of emissions on CO₂, SO₂, NO_x and particulate matters, but the reduction in SO₂, NO_x and particulate matters is greater in percentage than CO₂ reduction due to the fact that the fuel burning units use natural gas that has lower emission levels in particulate matters, NO_x and SO₂ compared to thermal stations that use Heavy Oil.
- ii.

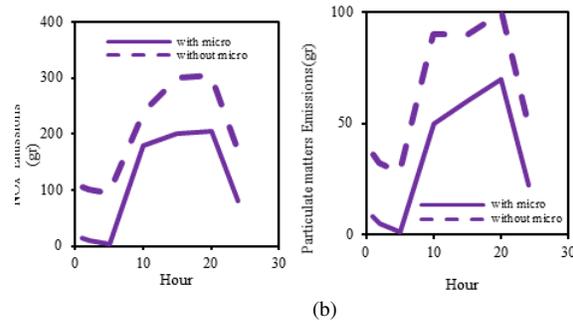
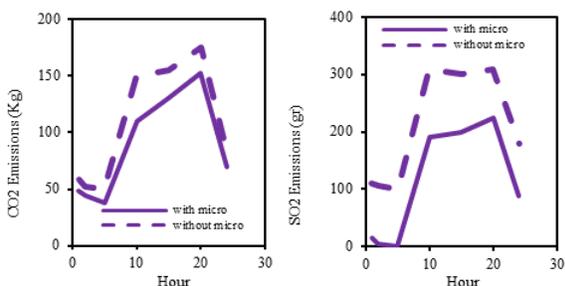
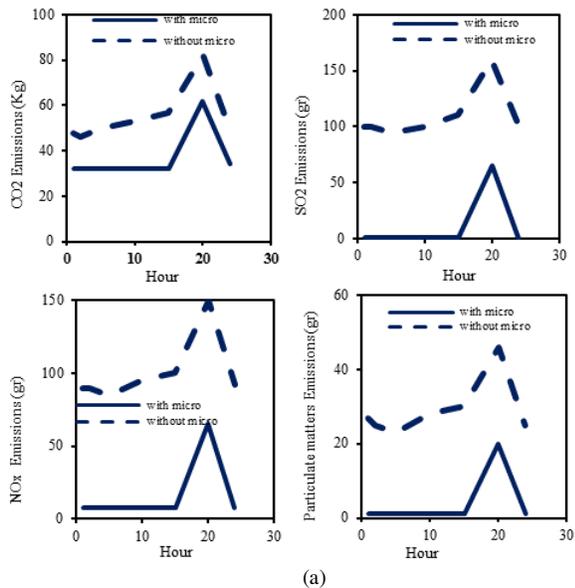


Fig.10 Amount of CO₂, SO₂, NO_x and particulate matters emissions for with and without μ sources, a. single feeder network b. Three feeders network

- iii. In our study, the amount of power produced by renewable energy is small (15% of the μ sources power), if the renewable sources increases, amount of emissions reduction will be more than the value shown in the previous figures.
- iv. The next step research aims to study the effects of micro grid in the dynamic performance of the main grid and how to use the μ sources to solve some of power system dynamic problems such as voltage stability, power quality and power system reliability.

IV. CONCLUSION

The effect on convective heat transport within a closed reservoir system of varying fluid composition was analyzed by CFD modeling of a single-phase fluid with properties derived from a composition-dependent average of pure CO₂ and pure H₂O. It is found that when the power produced by μ sources sufficient to loads, the voltage drop at all buses has a negligible values, also, using micro grid will decrease the amount of power losses because the power which produced by μ sources will consumed locally with the load near from the μ sources which prevent current from flowing or circulating in the networks transmission lines.

We conclude that this indicates substantial increase in convective heat transport. Convective heat transport may be further modified by multiphase flow behaviors, and we conclude that, due to the potential magnitude of heat flow enhancement by the addition of CO₂. From these findings, reservoirs with elevated CO₂ content will experience greater convective heat transfer and therefore be of comparatively higher temperature and therefore of greater resource value. Finally we can concluded any increase in CO₂ content of an existing reservoir will enhance convective flow behaviors although the true magnitude of this effect will depend on two-phase flow behavior as well as the particulars of the reservoir and consequently will enhance the productivity and/or the longevity of geothermal energy extraction. Results also showed that using μ sources has more effects in reducing all types of emissions especially when the μ sources contains many renewable sources such as wind and solar energy sources.



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