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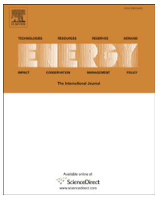

Investigation of novel, hybrid, geothermal-energized cogeneration plants based on organic Rankine cycle

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ABSTRACT

This paper presents and investigates several new hybrid integrations of Combined Heat and Power (CHP) plants driven by low-temperature geothermal water. Here, the main reason is optimization of the heat source utilization in vapor of promoting the net output power of Organic Rankine Cycle (ORC) as power plant operating in CHP models at variety of heating plant parameters. In order to evaluate and assess usefulness and importance scope of applying the new configurations, an exergetic and energetic analyses have been conducted. The simulations demonstrated that the power production has been considerably increased by the new CHP cycles, where optimization ratios could reach values till 130%, compared with conventional plants, at same heating plant conditions. Simultaneously, the heat source has been efficiently utilized by the hybrid models; where the exergy efficiency could register values till 71%. Finally, the new integration (HB4) is the lone hybrid principle which is characterized by its simplicity and enables high heat source exploitation flexibility and also provides possibility for maximizing the ORC power at the same heat demands and supply temperatures. Thus, this plant could produce 88% of the power generated by simple stand-alone ORC with total exergy efficiency of 70%.

1. Introduction

Although the geothermal heat resources are considered as one of the alternative energies, their utilization is largely similar to heat recovery principles from a waste heat stream, where in the both cases the useful output power must be maximized as much as possible for the energy unit available of these sources [1]. This strategy becomes more and more necessary when considering problems of fossil energy shortage along with augmenting the populations and the environmental considerations. Moreover, for meeting the different energetic requirements in case of local generation of the thermal and electrical energy in far regions from central energy production stations, the efficient exploitation of such resources seems to have more particularity. As instrument for mechanical and hence electrical power generation from such low-temperature resources, Organic Rankine Cycle (ORC) is the most mature and simplest technology. ORC was installed as stand-alone plant for sole power production or used in Combined Heat and Power systems (ORC-CHP) for producing the useful heat and mechanical power together from specific heat source. When ORC plant operates solely, its working parameters will be easily controlled to produce the maximal output power, where this muster was intensively researched for either geothermal or waste heat recovery applications [1–21]. While integrating ORC in Combined Heat and Power (CHP) systems will subject its performance to certain operation restrictions which are enforced by the heating plant requirements such as heat demands and supply and return temperatures. These restrictions will lead the ORC power to be kept away from the optimal desired values when connecting to the same heat source, even though utilization of the heat source will be more effective through CHP operation than through stand-alone ORC state as declared in the geothermal CHP applications [22–32]. Moreover, the CHP investigations, which paid some attention to the heating plant influences on the ORC plant productivity, demonstrated negative relations between the both plants. Heberle et al. [24] showed that price of electricity produced by ORC-CHP plant increases with raising the supply temperature, where this rise is caused by reducing the power productivity especially for the series integration and at low geothermal temperature. Khennich et al. [32] concluded that a higher heat fraction of the heat source is used as the heating load increases, where lower mechanical power will be submitted. The authors have extensively analyzed impact of the heating plant parameters on ORC performances and heat source

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utilization for three ORC-CHP plants fueled by low-temperature geothermal water [30,31]. They summarized that the ORC performance will be destructed when raising the heat demand and the return temperature and also at high supply temperatures. Also, the increasing return temperature and the high supply temperatures cause extreme heat source losses especially with exhausted streams at expense of power shortage for unchanged heat demands. Furthermore, the high supply temperatures limit the flexibility in the heat source utilization and power optimization in the series plant. All these observations can be considered as problems or negative aspects for the investments throughout the present ORC-CHP units.

In context of improving the utilization of the geothermal water, some studies of the CHP systems proposed novel arrangements of the plant integrations but only in favor of the heating plant enhancement. Heberle et al. [22,24] used an extra heat exchanger for additional heat generation in a hybrid plant for reducing the electricity price which is compensated by high heat production. Both Guo et al. [23] and Dragan et al. [28] integrated a compression heat pump after the heat exchanger of the heating plant for enhancing the heat load of the heat consumer, but this will reduce the pure outcome of ORC because of the electric current required for operating the heat pump. While the other ORC-CHP analyses did not argue extra utilizations of the exhausted streams, whereas they only screened a lot of working fluids in the common series and parallel model and sometimes compared the latter.

From the brief review presented above, it can be concluded that minimizing the irreversibility and also lowering the negative influences of the heating plant parameters on the ORC plant performance, as declared previously, will optimize the geothermal heat source exploitation throughout the cogeneration concept. Furthermore, it is to be expected that when the electrical power is essentially required along with the heat demands, especially when the other energy resources are not available, then promoting the power generation will be a promising goal. Nevertheless, all the previously cited ORC-CHP studies did not adopt new methodologies or thoughts for performing the mentioned purposes. So, this paper introduces and analyzes four hybrid connection concepts as optimization possibilities and problems' solutions of ORC-CHP integrations. Here, the main focus lies at enhancement of the power production of ORC power plant operating in these systems at expense of reducing the heat source losses, especially with the exhausted streams, at various heating plant parameters. Consequently, possibly eliminating the negative effects of the heating plant parameters on ORC output and also the effective exploitation of available low-temperature geothermal energy throughout cogeneration muster can be achieved. For comparison with the conventional series and parallel circuits, the latter along with the simple, stand-alone ORC (SSORC) will be also recalculated in this paper. Moreover, this study does not take the chemistry of the geothermal water into consideration because it imposes presence of so low-salinity geothermal water such as the Altheim/Austria plant heat source (almost fresh water) and also availability of corrosion-resistant materials which can be suitable for such evolutions. For evaluation, the net output power of ORC, the optimization ratio of the new plants versus the conventional ones, the exergy efficiency and the relative irreversibility with exhausted streams will be determined for variety of the heating plant parameters such as the return and supply temperature and also the heat demand. As working fluid in ORC, only the isentropic working fluid R134a will be used for simplifying the investigation and comparison; where the physical and thermodynamic properties of R134a can be obtained in the [33–35]. Finally, modulation and simulation of all cycles will be carried out by the software 'Matlab'.

2. Systems description

Fig. 1a–f shows the symbolic schemes of the hybrid configurations, under consideration, along with the conventional series and parallel one. According to this figure, it is obvious that all the hybrid concepts are characterized by the mixed or crossed integration of the heating and power plant (ORC) when connecting to the heat source (geothermal water) on the contrary of series and parallel concept, where a regular arrangement of the both heating and power system, with regard to the heat source, is followed. Nevertheless, all the illustrated CHP plants include the same mechanisms but with difference in the connection way or the number of parts, where the specialties of all the investigated hybrid units can be described and defined as below.

2.1. Hybrid plant characterized by additional preheater (HB1)

This configuration is considered as optimized version of the conventional series plant (SP), where an additional preheater, which can operate as an economizer for possibly recovering the waste heat carried by exhausted water, is integrated after the heating plant Fig. 1a. While this concept is not applicable on the SSORC or conventional parallel plant (**PP**) because ORC operates freely in these circuits at all pressure conditions and thus it can achieve its optimal power according to the available heat energy of the heat source. This development depends on understanding the power characteristic behavior of the stand-alone ORC plant under specific assumptions (e.g. R134a as working fluid and constant low-temperature heat source), where ORC power has an optimum when varying the evaporation pressure. While in case of CHP, the working pressure must be set at higher values than the optimal ones to enable high temperatures of the heat carrier at ORC outlet for meeting the heating plant parameters required, and consequently lowering the power production [23,30and31]. So, when recovering a fraction of the waste heat though the additional preheater of the power plant, the working fluid will enter the main preheater with temperature ($T_{2,2}$) which is higher than the condensation temperature (T_{co}) or the temperature after the pump outlet (T_2). Thus, the geothermal water will exit from the main preheater with higher temperature (T_{gwm}') than the needed one at the heating system inlet (T_{gwm}). This, in turn, enables a new setting of the working pressure in ORC, where the pressure can be declined (from P_{ev} to P_{ev}') at constant pinch point difference. This procedure leads to increase the power production with keeping adaptation of the geothermal water temperature at ORC outlet to the heating plant conditions (Fig. 2).

2.2. Hybrid plants characterized by additional evaporation systems (HB2, HB3)

These developments will be achieved through conjugating an extra evaporation system in the series circuit (HB2) and also in the parallel one (HB3) for enhancing the both conventional cycles (Fig. 1b and c). The main evaporator operates at high pressure, where it must be integrated before- (in case of HB2) or parallel to (in case of HB3) the heating plant regarding the heat source, while the additional one operates after the heating plant at low pressure. The additional evaporator will recover the heat losses as much as possible from the exhausted geothermal water throughout preheating and evaporating an extra amount of the working fluid. The latter is joined to the main mass flow rate of working fluid in turbine at low pressure level, where they will expand together for generating the useful power, Fig. 3. Although idea of using several evaporation systems on the same heat sources is well known and applied in case of stand-alone ORC [36,37], it has not yet been

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