Performance Analysis of a Steam Power Plant with District Heating

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Abstract:
District heating is a well-known application of sustainable development with respect to both economical and environmental aspects by increasing energy utilization. In this paper, a combined heat and power (cogeneration) system is created by adding a 14000-haused Can-Yenice district heating system after Can steam power plant in the North-west of Turkey. Its performance analysis is carried out to determine the most suitable pressure, temperature and mass flow rate combination of extracted steam with evaluation of different performance criteria as thermal efficiency, utilization factor, power output and heat exchanger area. It has been observed that all housings could be heated with the slight decrease of power output and efficiency that leads less natural gas and coal use for heating in the Can-Yenice district.

Keywords:
District heating, steam power plant, performance optimization.

1. Introduction

A district heating (DH) system could be defined as using hot water or steam to supply heat for house heating and domestic hot water demand. Generally, hot stream from a source is pumped to a heat exchanger where main district circulation water gains energy and distributes that energy to neighborhood branches. By another heat exchanger, mentioned branches deliver that heat to households in that area. District heating circulation water works at relatively low temperature. Usual temperatures of pumping hot water are between 80°C and 120°C and it returns at temperatures of 40 to 70°C [1]. Thus, different methods could be applied to provide hot water or steam for district heating system. Geothermal, solar and cogeneration energy systems are the most convenient used methods for DH heat source [2]. Mentioned renewable sources decrease fossil fuel need for heating sector [3]-[4]. However, they are not widely available.

Cogeneration means producing two outputs simultaneously from a system. Hence, cogeneration energy systems are used to generate both electricity and thermal energy and also mechanical energy when needed [5]. Combined heat and power (CHP) system is a type of cogeneration energy systems that produces process heat and power together by either using gas or steam turbine in a power plant. CHP can also be used with wind power system [6] and solar energy system [7]. Efficient and environmentally friendly energy conversion and utilization systems are gaining importance. CHP is one of the energy conversion systems that increase overall system efficiency [8]. The required Concurrent hot stream for DH in a CHP system could be produced via steam power cycle that obtains steam from waste heat steam generator after exhaust system of gas turbine power plant (GTPP) [9]. However hot stream is directly extracted from a steam turbine or a heat exchanger of steam turbine power plant (STPP) [4]. In addition to CHP, combined cooling, heating and power (CCHP) is also used in energy system. The definition and benefits of CCHP systems are explained and also utilization, developments and characteristics of CCHP technologies are displayed; then, different CCHP configurations of current technologies are described in [10]. Also CCHP system working with biomass gasification is analyzed according to exergoeconomic approach with respect to cost allocation and sensitivity and is studied in [11].

Recently, DH became an important status for residential sector with regards to its energetic and environmental aspects. DH system is analyzed in terms of energy and exergy methods, also advantages of DH are demonstrated in [12]. DH CHP and distributed generation CHP is compared in terms of environmental and economic criteria for Northern Italy in [13]. Erdem et. al [14] analyzed a coal-fired power plant in terms of suitability for trigeneration conversion, which is designed only for electricity generation. They evaluated waste heat potentials and other heat extraction capabilities. They demonstrated optimal steam extraction point for DH in aspects of energetic and exergetic performance. Also Erdem et. al [15] evaluated renovation of power plants to co/tri-generation systems for DH for different criteria including electrical power output, classical thermal efficiency, coefficient of performance (COP) and comprehensive thermal efficiency. Gadd and Werner [16], [17] studied on the heat load patterns and they find that applied control strategy, season and customer category effect on normal heat load patterns. Persson and Werner [18] evaluated excess heat utilization in DH within EU27 with respect to recovery efficiency, heat recovery rate, and heat utilization rate. Also they [19] also analyzed the future competitiveness of DH considering capital cost of city characteristics, city sizes, and heat demands. There are some optimization studies to increase efficiency of DH in the literature. A alternative control method for DH substations was described and this new method leaded to increased temperature differences across the substation [20]. Also Steer and Halgamuge [21] improved the operating costs via appropriate control period selection.

In this paper, a CHP system is created with 14000 housing in Can-Yenice cities which are the closest cities to Can thermal power plant in south-west Marmara region, Çanakkale province. Performance analyses are carried out for six different cases with respect to the hot stream extraction points in power plant. Parametric studies are performed considering the environmental temperature, temperature difference between district inlet and inside comfort temperature, and inside comfort temperature to evaluate thermal efficiency, utilization factor, power output and heat exchanger area as performance criteria.

2. Method

Can Thermal Power Plant and district heating system are investigated in terms of first law of thermodynamics. Produced power in a stage of an adiabatic turbine is calculated as when potential and kinetic energies are neglected:

$$\dot{W}_T = \left(\sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e\right)\eta_m \tag{1}$$

where $\sum_i \dot{m}_i h_i$ is the total energy of inlet streams, $\sum_e \dot{m}_e h_e$ is the total energy of outlet streams and η_m is the mechanical efficiency of the turbine. Total produced shaft power as:

$$\dot{W}_{TOT} = \dot{W}_{HPT} + \dot{W}_{IPT} + \dot{W}_{LPT} \tag{2}$$

where subscript *TOT* stands for total produced shaft power, *HPT, IPT*, *LPT* stand for high, intermediate and low pressure turbines respectively. Generated electricity is:

$$\dot{N}_e = \dot{W}_{TOT} \times \eta_{gen} \tag{3}$$

where $\dot{N}_e$ is electricity and η_{gen} is generator efficiency. Given heat by boiler $\dot{Q}_H$, could be calculated by using boiler efficiency η_{boil}, energy streams that enter and exit the boiler as below:

$$\dot{Q}_H = \frac{(\sum_e \dot{m}_e h_e - \sum_i \dot{m}_i h_i)}{\eta_{boil}} \quad (4)$$

with respect to the heat demand $\dot{N}_q$ and condenser heat transfer $\dot{Q}_{Con}$, district heating system total surface area A_{DH}, and condenser heat transfer area A_{Con}, can be calculated by heat transfer equations [22] for simple type heat exchangers:

$$A_{DH} = \frac{\dot{N}_q}{U_{DH} LMTD_{DH}} \quad (5a)$$

$$A_{Con} = \frac{\dot{Q}_{Con}}{U_{Con} LMTD_{Con}} \quad (5b)$$

where U_{DH} is universal heat transfer coefficient for DH system heat exchanger and $LMTD_{DH}$ is logarithmic mean temperature difference of DH system heat exchanger; U_{Con} is universal heat transfer coefficient for condenser and $LMTD_{Con}$ is logarithmic mean temperature difference of condenser. Total heat transfer area and relative change of total area are:

$$A_{Tot,k} = A_{DH,k} + A_{Con,k} \quad (6a)$$

$$A_{rel} = \frac{A_{Tot,case\ 1} - A_{Tot,case\ k}}{A_{Tot,case\ 1}} \quad (6b)$$

Relative change of total area is calculated as the ratio of the difference between total area of base case 1 and the total area of cases 2 to 6 to total area of base case 1.

Efficiency is a very useful tool to evaluate the performance of any power producing system via first law of thermodynamics and it may be defined as the ratio of desired output to the required input of the investigated system [23]:

$$\eta_{th} = \frac{\dot{N}_e}{\dot{Q}_H} \quad (7)$$

Similarly, a utilization factor which includes both heat and electricity load could be defined as:

$$f_u = \frac{\dot{N}_e + \dot{N}_q}{\dot{Q}_H} \quad (8)$$

3. System Description

Can thermal power plant is located in Çanakkale the South-west Marmara region in Turkey and designed to produce electricity to fulfill 320 MW of electricity demand of Turkey with its two-generation units [24]. In one unit, it has low, intermediate and high-pressure turbines, boiler, feedwater heaters, pumps, deaerator and condenser as seen in Figure 1. In short, superheated steam is sent to high-pressure turbine from boiler and expanded to intermediate pressure. A part of steam is sent to feedwater heater to heat water before boiler and rest of the steam is sent to reheater. Reheated and intermediate-pressured steam is expanded through intermediate turbine while two fractions of steam are extracted for feedwater heaters and deaerator. Expanded steam is partly sent to low pressure turbine. Steam extraction processes also occur in this component. After that, saturated liquid-vapor mixture is condensed in the condenser and pumped through feedwater heaters. Finally it completes the cycle in the boiler by being superheated.

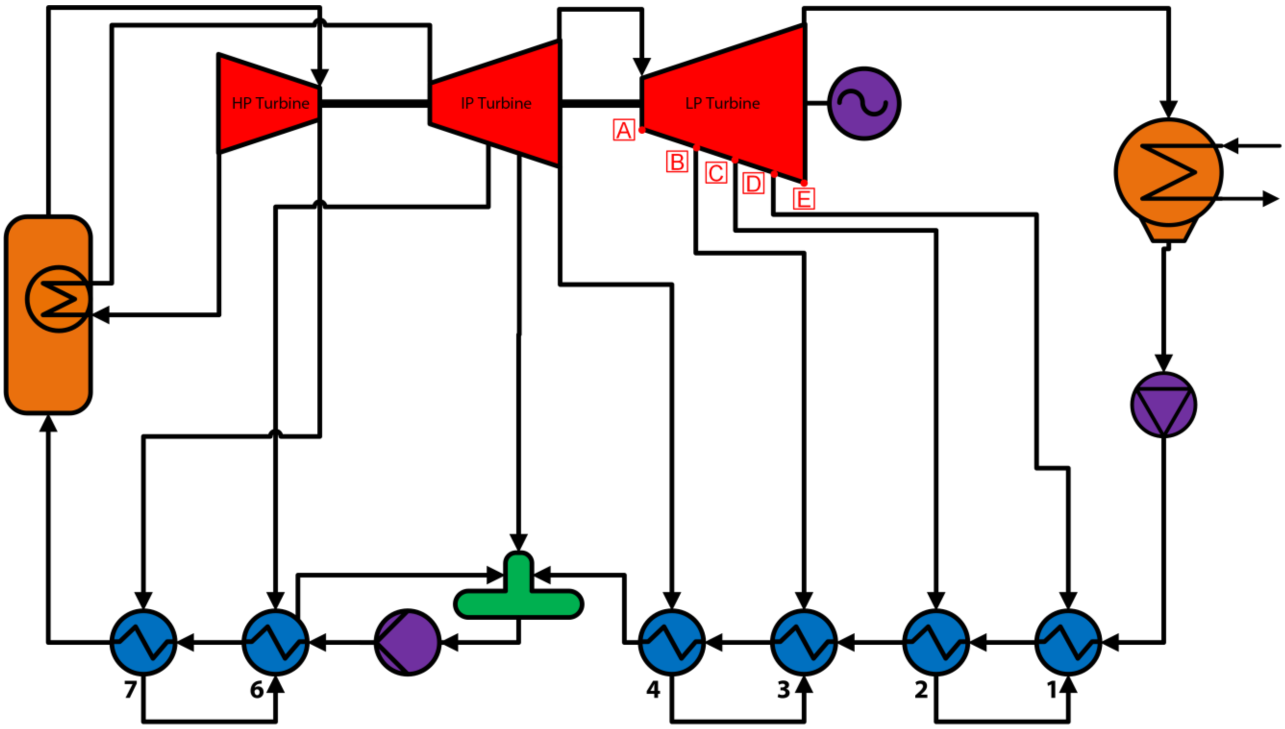

Fig. 1. Simplified general schematic of Can thermal power plant

Since Çan and Yenice are the closest cities to the Can Power Plant, an opportunity of district heating (DH) system for these cities is evaluated. DH system is designed for approximately 14000 housings with average heat demand of 107 MW [14] and separated to same hypothetical branches and sub-stations for each neighborhood. Five steam extraction points for district heating system are identified as low-pressure turbine inlet, its extraction points and heat extraction from condenser. Extracted hot stream is directed to district heat exchanger station that represents total heat exchangers in all sub-stations of branches as seen in Figure 2. After energy of hot stream is used to heat district-heating circulation water, pressure of cooled stream is decreased by expansion valve to return to the power plant. The required thermal load of district heating is fulfilled with stream energy. It is adjusted by mass flow of hot stream, which is extracted from STPP. Mentioned stream returns to condenser of STPP after requirement is fulfilled. By assuming a representative DH station, all piping, pumping, heat exchanging loads and losses of sub-systems are evaluated in it. Hence, a change in the area of DH station represents all branch sub-stations and pipes. Domestic hot water usage is neglected since this paper deals only with the district heating.

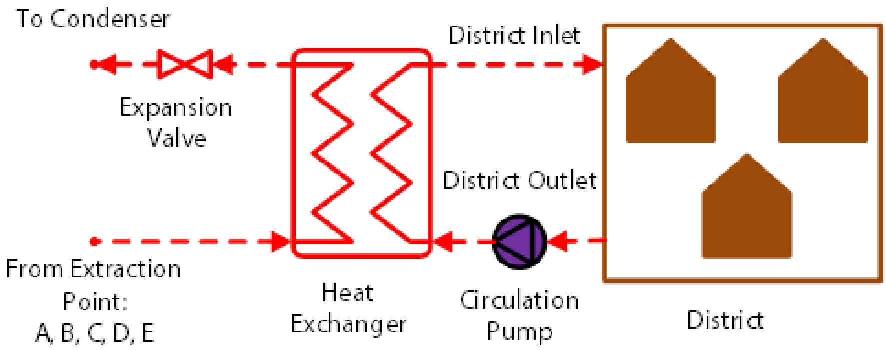

Fig. 2. Simplified general schematic of district heating system

Six different cases are created to analyze combined heat and power system as follows:

1. No addition of district heating as a base case for comparison.

2. Steam extraction from inlet of low pressure turbine, point A
3. Steam extraction from point B
4. Steam extraction from point C
5. Steam extraction from point D
6. Heat extraction from condenser, point E.

In all cases, extracted mass flow rate and properties of steam are also determined to fulfill heat demand. Information about the cases described above could be seen on table below for base heat demand 107 MW:

Table 1. Properties of extracted hot streams for each case

Case	Pressure (bar)	Temperature °C	Mass flow rate (kg/s)
1	-	-	-
2	5.192	278.5	37.68
3	1.954	178	40.42
4	0.5249	82.55	43.74
5	0.2687	66.6	45.4
6	0.085	42.67	48.24

The region under investigation has a meteorological profile that varies monthly between 6.3 – 25.1 °C for time interval 1950-2014 [25] as it can be seen on Figure 3. Blue bar represents average monthly temperature in the region of Çanakkale and upper limit of black line is average maximum temperature while lower limit represents minimum average temperature. It is assumed that 107 MW heat load belongs to the 5°C environmental and 25 °C inside comfort temperatures at Çanakkale province.

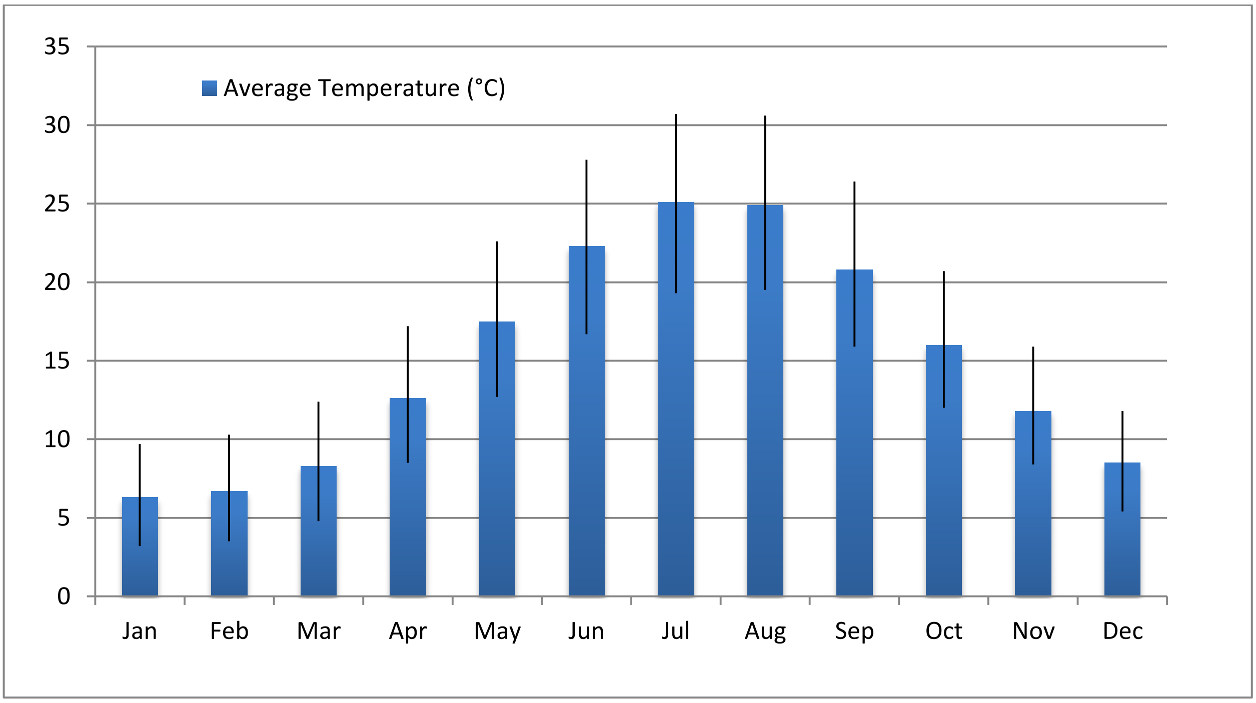

Fig. 3. Average environmental temperature of Canakkale province.

Changing extraction point of the heating steam changes the mass flow rate regarding the temperature and the pressure of the point itself as it could be seen in Table 1. Also, heat exchanger area varies by each case related to mass flow rate and the temperature of the heating steam. Beside all six cases, monthly average temperature in the region is identified as another parameter for the designed CHP system. The effect of varied environmental temperature will directly affect and varies the average heat demand of DH system and also utilization factor. Thus, it directly affects heat exchanger area of the station and mass flow rate of the heating stream. Environmental temperature T_{env}, is varied between 5 ℃ and 15 ℃ as parameter that includes six months. Also, temperature difference between inside comfort temperature and district inlet temperature $T_{DH,in}$, varies between 40 ℃ and 60 ℃ as second parameter. Lastly, the third parameter is inside comfort temperature T_c, which varies as 23 ℃, 25 ℃, and 27 ℃.

4. Results and Discussion

First, the effects of changing inside comfort temperature on criterion are evaluated by keeping T_{env} = 5℃, ($T_{DH,in}$ - T_c) = 15℃ constant. As it can be seen in Figure 4, inside comfort temperature is chosen as primary parameter. Its effect on the utilization factor and the thermal efficiency has been evaluated as the lowest thermal efficiency belongs to case 2 for each T_c due to high quality steam extraction from inlet of the LPT. Case 1 and 6 have the same thermal efficiencies, because hot stream extraction is only from condenser in case 6, hence it does not affect the electricity production. For cases 2-5, it is observable that when T_c increases, thermal efficiency decreases and utilization factor increases because of increasing heat load of DH. In addition, thermal efficiency and utilization factor are increasing with respect to the cases from 2 to 6 respectively related to decreasing of hot stream energy quality. Lastly, utilization factor is always higher than thermal efficiency for cases 2 to 6.

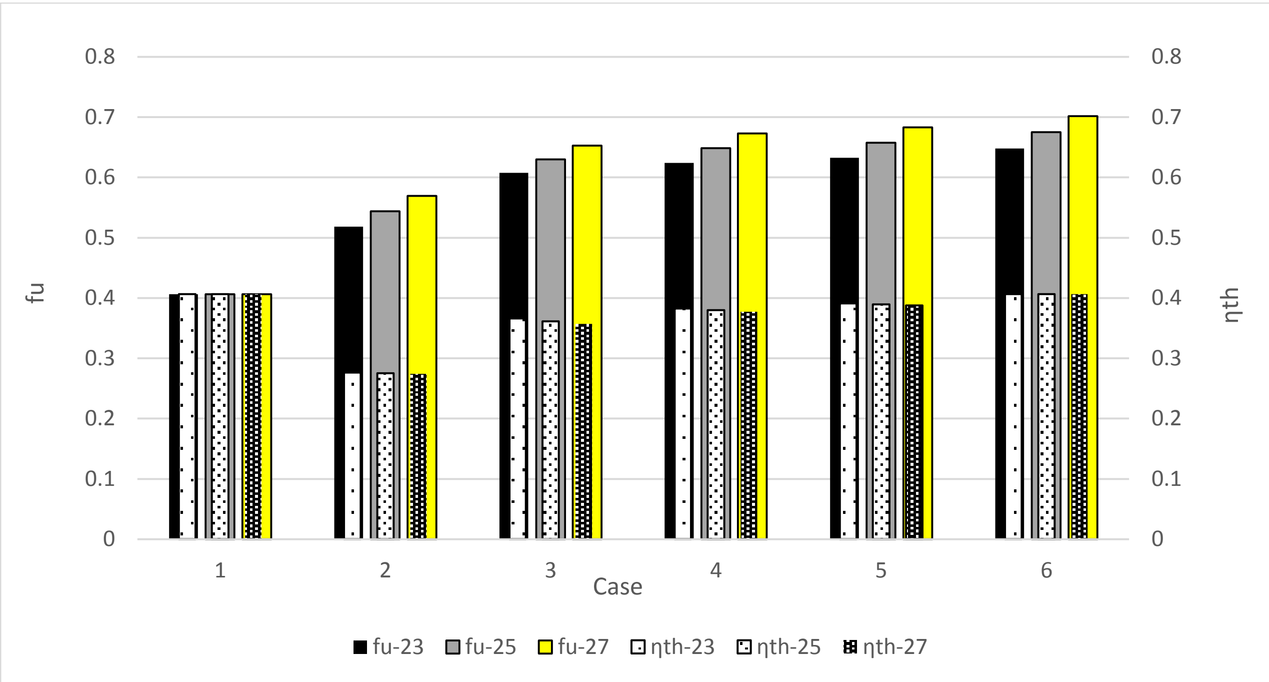

Fig. 4. Utilization factor and thermal efficiency with respect to the cases and inside comfort temperature.

In Figure 5, when T_c increases, heat load also increases due to increase of temperature difference between T_c and $T_{env.}$ Heat load only depends on this temperature difference so that it has the same values for each case from 2 to 6. Similarly, with Figure 4, electricity loads of cases 1 and 6 have exact same value. It is obvious that electricity load in Figure 5 has the same trend with thermal efficiency in Figure 4.

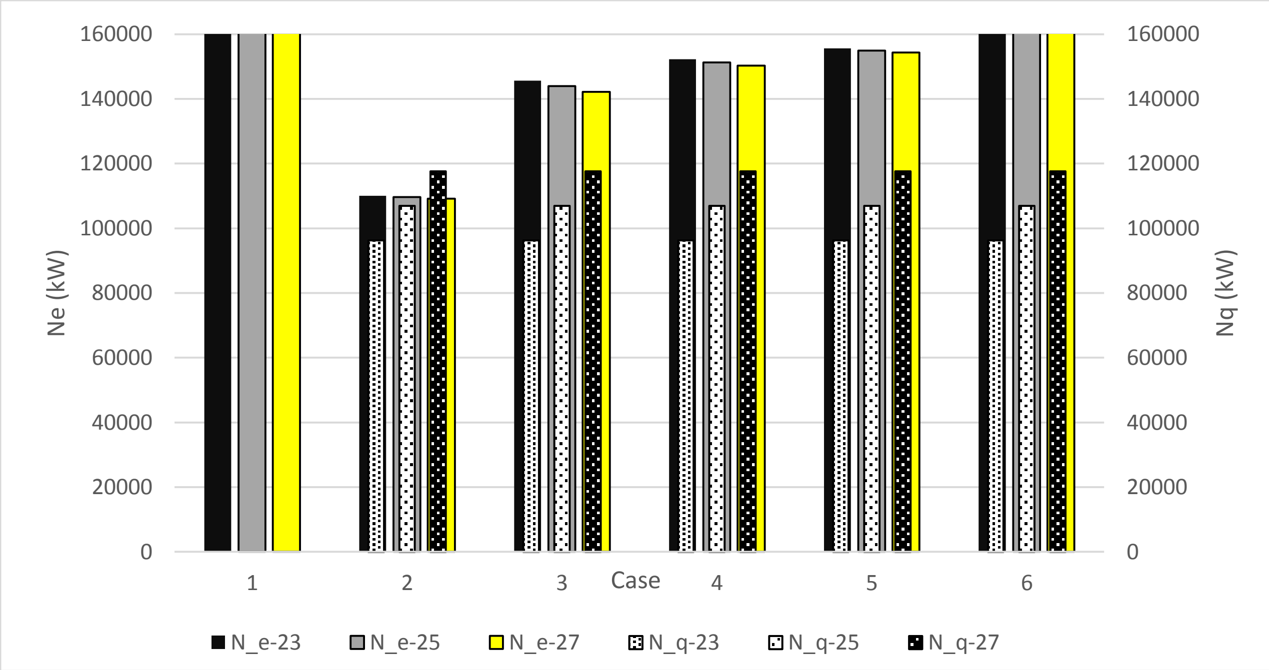

Fig. 5. Heat and electricity loads with respect to the cases and inside comfort temperature.

As the base case, there is no DH heat exchanger area in case 1 shown in Table 2. Minimum DH heat transfer area belongs to case 2 for all inside comfort temperatures. However, minimum total heat transfer area is in case 3. That is the result of higher enthalpy of hot stream returning to condenser, which increases heat transfer area of condenser comparing to other cases. Maximum DH heat transfer area and minimum condenser area are in case 6 for all temperatures.

Table 2. Heat transfer areas of condenser, DH with respect to the cases and inside comfort temperature.

Case	A_Con-23	A_DH-23	A_Tot-23	A_Con-25	A_DH-25	A_Tot-25	A_Con-27	A_DH-27	A_Tot-27
1	3923	0	3923	3923	0	3923	3923	0	3923
2	2750	274,3	3024,3	2620	308,4	2928,4	2490	343,4	2833,4
3	2558	429,7	2987,7	2406	486,2	2892,2	2254	544,9	2798,9
4	2310	975	3285	2130	1129	3259	1951	1297	3248
5	2203	1444	3647	2011	1707	3718	1820	2007	3827
6	2004	5509	7513	1791	8326	10117	1578	16264	17842

Secondly, environmental temperature has accepted as a parameter by keeping T_c = 25℃, and T_{DH} = 40 ℃ constant due to their interconnection ($T_{DH,in}$ - T_c =15℃) with each other. Effects of this parameter are shown in Figure 6.

As it can be seen on Figure 6, utilization factor decreases and electricity load increases with increasing environmental temperature, because lower temperature difference between T_c and T_{env} leads lower heat load. Comments could be made on ranking of cases as the highest utilization factor belongs to case 6 although minimum belongs to case 1. For case 2, second lowest utilization factor and electricity load is observed due to high quality hot stream.

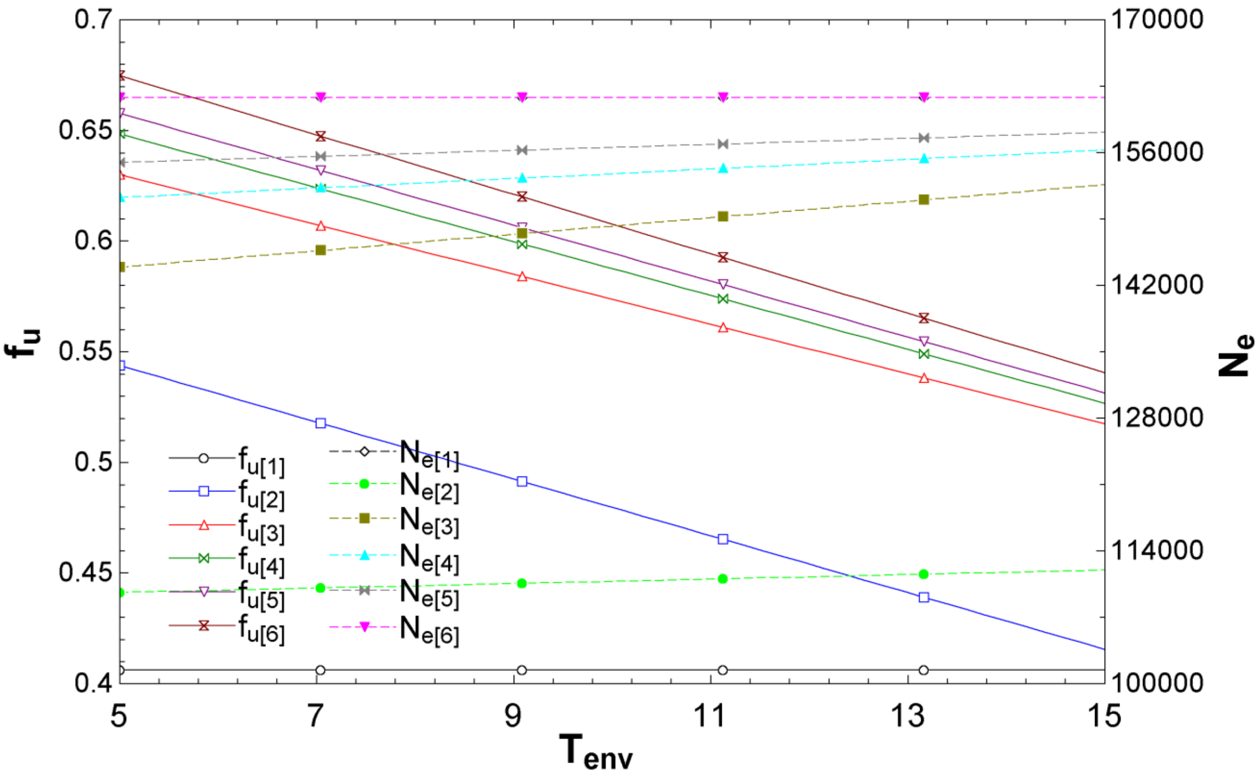

Fig. 6. Utilization factor and electricity loads with respect to the environmental temperature.

In Figure 7, thermal efficiency shows the same trend with electricity load in Figure 6, hence similar comments could be made on it. When T_{env} increases total heat exchanger areas of cases 2-5 are increase. Nevertheless, total heat transfer area of case 6 have a tendency to decrease. In Figure 8 as a detailed heat exchanger area variation, decreasing heat load directly affects and decreases the required mass flow rate for DH system. Hence, mass flow rate goes through the condenser increases. Thus, heat exchanger area of condenser also increases. The high decreasing slope of DH area causes dramatic decrease of total area at case 6.

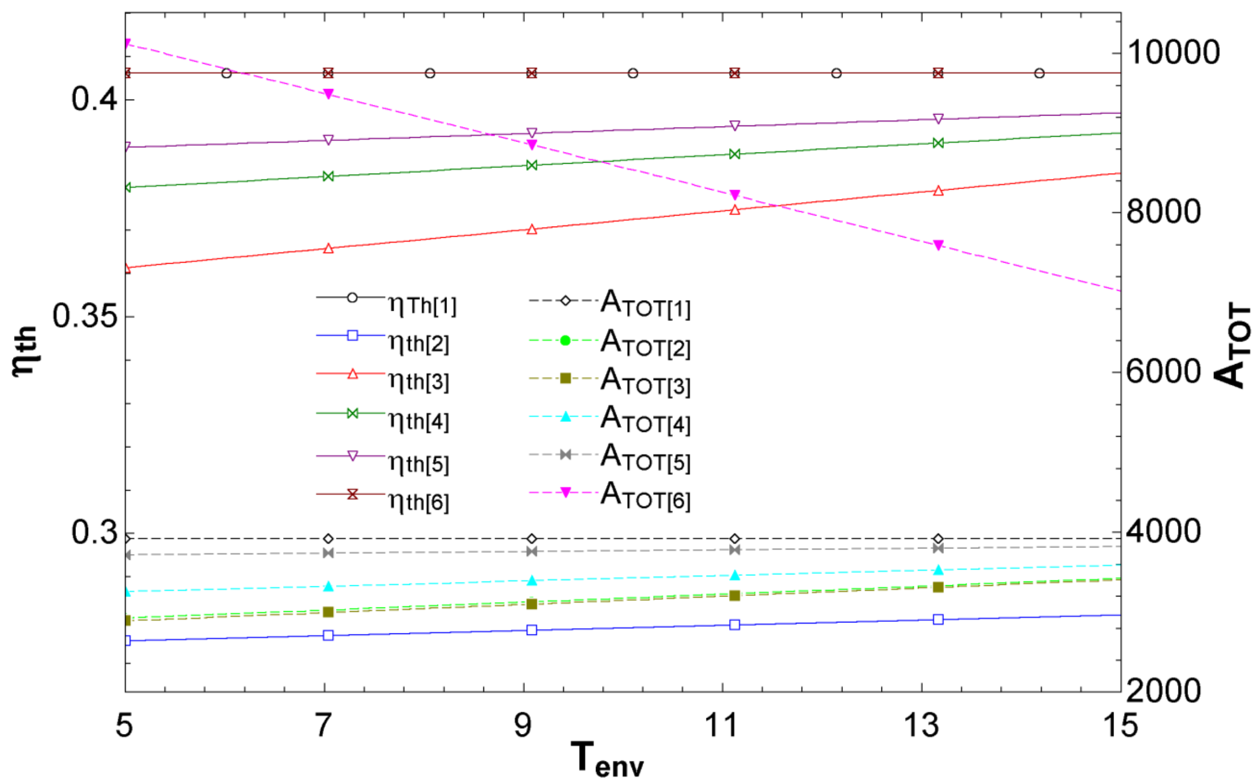

Fig. 7. Thermal efficiency and total heat exchanger area with respect to the environmental temperature.

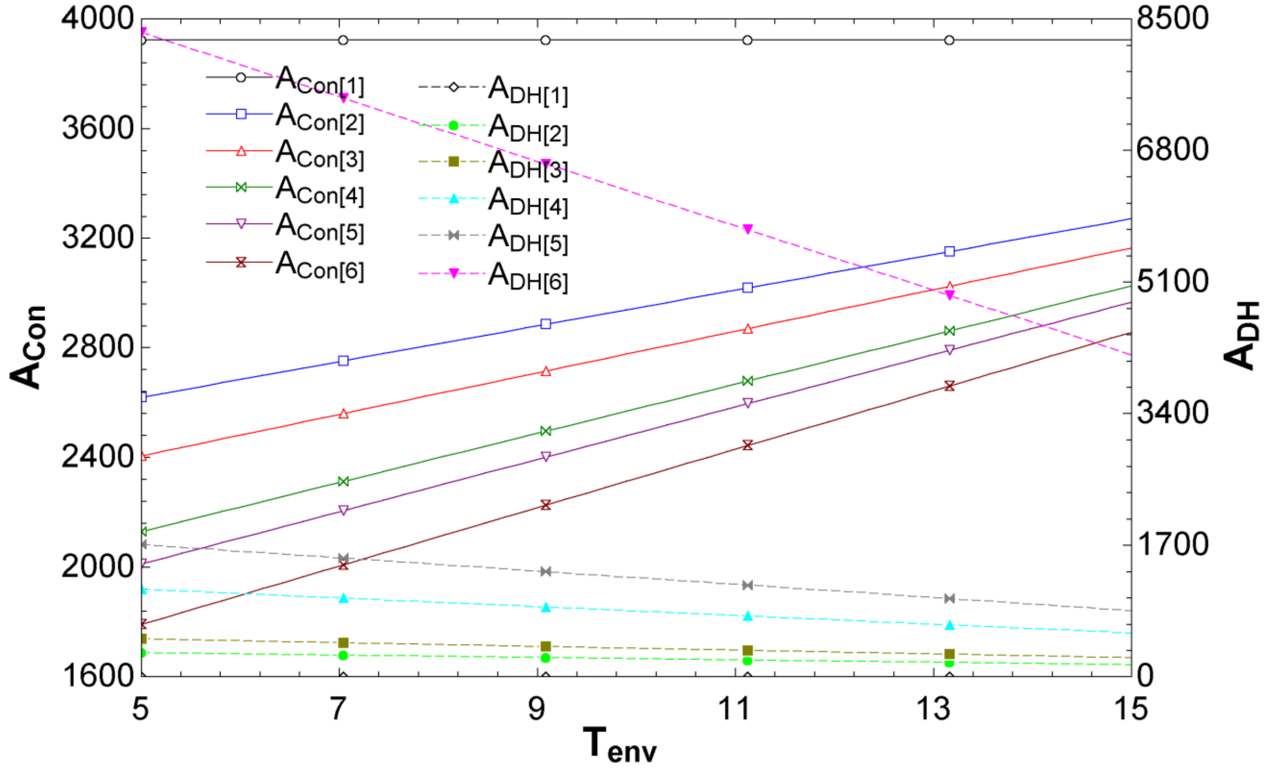

Fig. 8. Condenser and DH heat exchanger area with respect to the environmental temperature.

Lastly, district heating inlet temperature has accepted as parameter by keeping T_c = 25°C, T_{env} = 5°C, while $T_{DH,in}$ varies between 40°C to 60°C. Effects of this parameter on condenser and DH heat exchanger area could be seen in Figure 9. Inlet temperatures, mass flow rates coming from power plant are constant for each case. This explains why the condenser area does not change with the changing of $T_{DH,in}$. This situation is same for other criteria except DH heat transfer area. While $T_{DH,in}$ increases, DH heat transfer area also increases due to increase of logarithmic mean temperature difference of DH heat exchanger. Case 6 draws an unusual profile. Because it takes hot stream directly from condenser and inlet temperature of condenser is around 43 °C. If $T_{DH,in}$ reaches the same temperature then DH heat transfer area goes to infinite while condenser area is constant.

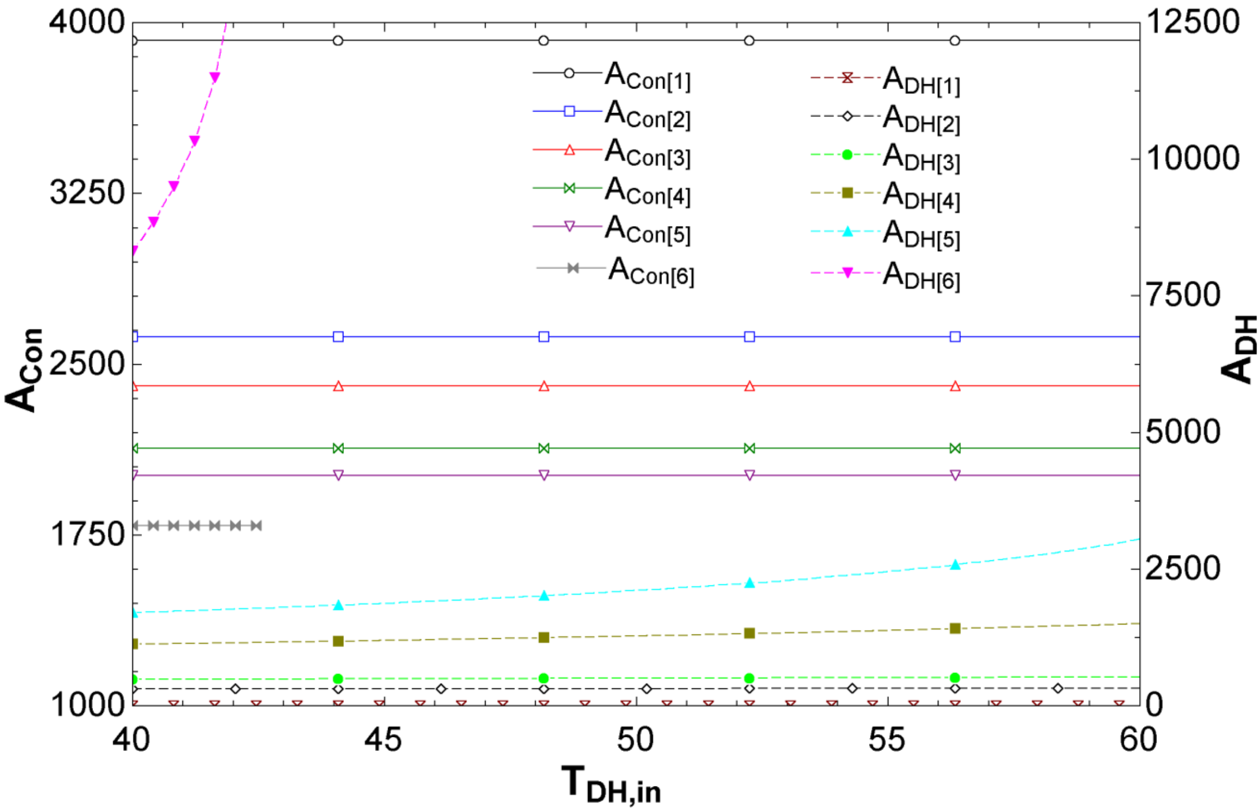

Fig. 9. Condenser and DH heat exchanger area with respect to the DH inlet temperature.

5. Conclusion

In this paper, a DH system added after a steam turbine power plant is investigated with the parameters of environmental temperature, inside comfort temperature of the district and district heating inlet temperature for six different cases that include 5 different hot stream extraction points. It is observed that utilization factor increases and thermal efficiency decreases with increase of heat load, which is directly connected to inside comfort and environmental temperature. Moreover, heat exchanger areas are directly affected by comfort and environmental temperature variation and hot stream quality. It is found that the hot stream quality is a highly important variable for this type of application. DH inlet temperature only affects DH heat exchanger area, and there is no connection with other criteria.

Future work will be conducted as economical and environmental analysis of this work and also, exergy, exergoeconomic analyses will be carried out.

6. References

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