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Research Paper

Feasibility of using vapor compression refrigeration system for cooling steam plant condenser

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HIGHLIGHTS

- A refrigeration system is proposed to cool the condenser of a steam power plant.
- Thermal efficiency improvement of 1.2–12% is achieved.
- The specific refrigerant mass does not depend on the ambient temperature.
- The specific refrigerant mass runs linearly with steam condenser temperature.

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ABSTRACT

This study presents a proposal of a combined scheme for applying a vapor compression refrigeration system to cool the condenser of a steam plant. In this scheme the refrigerant (mostly liquid) leaving the throttle valve of the refrigeration system is circulated through the pipes of the shell and tube condenser, while the steam exhausting the plant turbine flows in the shell around the outer surfaces of the tubes. Thus, the refrigerant is vaporized and the steam is condensed. As a result, the maximum coefficient of heat transfer between the steam and refrigerant is achieved, and the condenser becomes compact. In addition, this combined scheme allows controlling the condenser temperature irrespective of the ambient conditions. Thermodynamic analysis of the steam plant, vapor compression refrigeration system and the proposed combined scheme has been developed. The results obtained using this analysis showed that an improvement in thermal efficiency of the combined scheme varying between 1.2 and 12% is achieved over that of the steam plant when the condenser is cooled, using ambient air, for the range of the ambient temperature of 30–50 °C and condenser temperature of 15–50 °C. The high value of the improvement is valid for higher ambient temperature and lower condenser temperature. Also, the results indicated that the specific refrigerant mass (mass of the refrigerant needed for condensing 1 kg of the steam) varies between 1.42 and 1.62 kg/kg at condenser temperature of 15 and 50 °C, respectively. This specific mass does not depend on the ambient temperature and runs linearly with steam condenser temperature.

1. Introduction

Steam power plants provide most of the world electricity. In these plants, water is heated in a steam generator or boiler to steam that is used to drive a turbine-generator. Steam exhausted from the turbine has to be inevitably condensed and sent back to the steam generator/boiler. The steam condensation occurs in a steam condenser. Cooling water mass flow rate of greater than 25 times the steam mass flow rate is necessary depending on the allowable temperature rise of the cooling water – typically 8–14 °C. There are basically two types of cooling water system designs – once-through (open loop) or re-circulating (closed loop). Plants equipped with once-through cooling water systems have relatively high water use in the range of 3 m^3/min for each MWe, and they cause a critical detrimental impact on aquatic ecosystem [1].

The most common type of re-circulating system uses wet cooling towers to dissipate the heat from the cooling water to the atmosphere. This type requires a supply water make-up rate of about 5% [2]. In addition, cooling water is the major source of wastewater generated by most thermal power plants. For each MWe of a facility about 7.5 m^3 per day of waste water are generated, with about 70% of this waste water coming from cooling tower blow down [3].

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Nomenclature

COP	coefficient of performance
h	specific enthalpy (kJ/kg)
m	mass (kg)
t	temperature (°C)
T	absolute temperature (K)
w	specific work (kJ/kg)

Greek letters

$\Delta T_{rc,ss}$	elevation of the condensate saturation temperature over the saturation temperature of the cooling refrigerant in the steam condenser/evaporator of the studied system
$\Delta T_{rc,wc}$	elevation of the condensate saturation temperature over the saturation temperature of the cooling refrigerant in the steam condenser/evaporator of the studied system
$\Delta T_{sc,rs}$	elevation of the condensate saturation temperature over inlet temperature of the cooling air in the steam condenser of the reference system
η_m	mechanical efficiency
η_{th}	thermal efficiency

Subscripts

a	ambient
b	boiler
ac	air cooled
co	compressor
c	condenser
e	evaporator
g	generator
p	pump
r	refrigerant
rc	refrigerant condenser
rs	reference system
s	steam
sc	steam condenser
sc-re	steam condenser/refrigerant evaporator
ss	studied system
t	turbine
wc	water cooled
1–16	state numbers of the steam/water of the steam cycle and refrigerant of the refrigeration cycle
I, II	compressor no. I and II, respectively

Abbreviations

LLSL-HX	liquid-line suction heat exchanger
SPP	steam power plant
SPPC	steam power plant condenser
VCRC	vapor compression refrigeration cycle
VCRS	vapor compression refrigeration system

Due to enhanced concern about the extremely detrimental water pollution of the thermal power plants, water supplies and water use priorities, dry cooling systems for thermal power plants are receiving increased consideration, even though electric power from dry-cooled power plants currently costs 10–15% more than power from wet-cooled plants [4]. There is little current research and development work being reported in the literature on dry cooling systems for power plants. A few important exceptions include improved heat exchanger geometries for finned tube bundles in air-cooled condensers [5,6]; enhancement of air-cooled condenser performance with the use of limited water [7,8]; the use of evaporative condenser [9]; optimization techniques [10]; and using double wet and dry condenser, where the heat of the wet condenser is dissipated into a cooling storage container [11].

The concept of the ammonia dry cooling system is reported in [12]. The system is an indirect type, in which the usual circulating water loop is replaced by a phase-change ammonia loop, where the ammonia is evaporated in the tubes of the steam condenser and condensed in an air-cooled condenser. This concept was tested and well documented [13–15], with the participation of several major equipment vendors (Baltimore Air Coil, The Trane Company, Curtiss-Wright, CB&I, and Union Carbide). To date, the concept has not been pursued commercially, but may bear reexamination in light of increasing interest in economical dry cooling.

It is noted that most of the power generated during peak-load periods is used for driving the refrigerant compressor. This resulted in a great inefficiency and the demanded load would not be covered during this period. For overcoming this problem, it was proposed in [16] the use of cold storage system with the combined steam plant and refrigerating cycle described in [12]. This modification allows utilizing the discounted rates for energy during off peak-loads to produce cooling that is stored in the cold storage container. Over the period of the peak-loads, the refrigeration machine is stopped and the cooling refrigerant dissipates the heat absorbed from the steam condenser into the cooling storage system. This allows the whole power generated by the steam power plant to be exported to the grid.

The above described background leads to evaluating the concept of dry cooling of a SPPC by a refrigeration system. It showed that a study is necessary for testing the performance of the cooling method in connection with the steam power plant performance and ambient conditions. Naturally, refrigerants have much lower temperatures and much higher heat transfer rates than water or air. A theoretical study was performed in [17], which determined that R-134a is a superior coolant to water in SPPC. This study was followed by a comparative investigation between using R-410A, R-407C, R-22, and R-134a as cooling mediums to select the best efficient refrigerants for SPPC [18]. Based on these two analytical studies, R-410A was determined to be the best refrigerant for SPPC cooling. Accordingly an experimental research was carried out [19] for testing the possible use of a vapor compression refrigeration system to cool the condenser of steam plant. In this research, a 10 kW steam condenser, cooled by R-410A vapor compression refrigeration system, was designed, constructed and tested. The experiments executed in [19] revealed the problems which may be encountered in using such a refrigeration system to cool the condenser of a steam plant and discussed the possible solutions to these problems.

The current work presents an analytical study for predicting the performance of a steam power plant with a steam condenser cooled by a vapor compression refrigeration system under different operating conditions. The results of this study will lead to evaluating the technical features of putting such combined system into practice.

2. Reference steam power plant system

The functional principle of the steam power plant (SPP) follows a Rankine cycle. In this cycle, it is indispensable to sustain a low temperature reservoir to turn away some of the heat gained in