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Integration of absorption refrigeration systems into Rankine power cycles to reduce water consumption: A thermodynamic analysis

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A B S T R A C T

A high percentage of the heat that is supplied to thermoelectric power plants is discarded to ambient and must be handled by an external cooling system. This cooling system typically consists of wet cooling towers because of the excellent thermo-physical properties of water. However, the amount of water consumed for power production has reached alarming levels in developed countries. Air-cooled heat exchangers (ACHXs) appear to be the most adequate technology to substitute for wet cooling towers, but the use of this technology has some limitations. The most important limitation is the higher condenser pressures in the cycle, which produce backpressures at the condensing turbine's exit, increases in heat rejection and losses in the net plant efficiency. This paper presents a concept for the use of ACHXs in the cooling systems of power plants using an absorption refrigeration system (ARS) as an intermediary. Heat from the steam condenser is handled by the evaporator of the ARS and "lifted" to a higher temperature level, where the ACHXs are fitted to work. The generator of the ARS is fed by the power plant itself, extracting (bleeding off) some of the steam that flows through the steam turbine at the correct pressure and temperature.

1. Introduction

People's demand for comfort has strong ties to the availability of electrical energy, which is reflected in the increasing popularity of consumer electronics, home appliances, and heating-ventilating-air conditioning (HVAC) systems. Moreover, the production of electricity has stronger ties to the use and consumption of water because large quantities are required for heat rejection purposes in thermal power plants [1,2]. For some years, water has been recognized as a scarce resource in a significant portion of the world. Some publications have warned that water stress will become a severe problem in the next decade [3,4]. Of the total available water in the world, 97.5% is saline water and the other 2.5% is freshwater. Seventy percent of the freshwater is contained in ice caps and glaciers, leaving only 30% of the 2.5% for human use [5].

As the population growth exceeds 7.4 billion worldwide [6], new unconventional power plant technologies (e.g., solar thermal power plants, desalination within power generation, waste-to-energy power plants, organic Rankine cycles (ORC), and single- or solar-powered ejector refrigeration systems (ERS) combined with a power cycle) are emerging to satisfy the efficient production of electricity and the lower consumption of freshwater in energy-related processes [7–10]. For example, 41% of the freshwater withdrawal in the U.S. in 2010 was for thermoelectric power generation purposes [2,11]. Most of the technology that is used currently for electrical power generation worldwide relies on fossil fuels (40.6% coal, 4.7% oil, and 22.2% gas) [7,11], with conversion efficiencies ranging between 35% and 55%. In other words 45%–65% of the heat input in these plants is rejected to the environment as unprofitable waste heat. In the U.S., 99% of this heat is handled by water cooling technologies [12].

Two standpoints exist for power plant cooling purposes: air-cooled and water-cooled heat exchangers [8]. Water has better thermo-physical properties than air from a heat absorption

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perspective (i.e., a 4-times-higher specific heat and 24-times-higher thermal conductivity at room temperature), so water-cooled heat exchangers are preferred. These devices can provide lower condensing temperatures, enabling greater plant operating efficiencies.

Water cooling technologies can be separated into two main areas: open- and closed-loop systems. Open-loop or *once-through* systems take water (fresh or saline) from an artificial or natural water reservoir; the water is heated as it circulates through the condenser and returns to its source downstream. The discharge temperature of the water back to the reservoir should not be more than 32 °C in the U.S. [13,14], which limits the maximum change in the cooling water temperature through the condenser to approximately 10–12 °C to minimize harmful effects on life in water ecosystems. This requirement implies that large amounts of water must be withdrawn from the source, approximately 40–50 times the mass flow of steam to be condensed (depending on the condensing temperature) when considering only the latent heat of vaporization of the water. Nevertheless, the water consumption in this type of cooling technology is relatively low compared with that in other methods [1,2]. Wet closed-loop systems recirculate water from the same source (cooling tower or water pond) but rely on the evaporation of a certain amount of water to produce a cooling effect. Changes in the temperature of the cooling water are no longer an impediment in cooling tower technology, and lower amounts of water must be recirculated. However, this consumption increases by approximately 1%–5% of the recirculating water flow because of evaporation, drift and blowdown that is associated with the operation [15,16]. Higher evaporation rates can be registered in water ponds because of the convection to ambient air on the large exposed surface area. Evaporation rates largely depend on the on-site climate conditions, so significant water consumption fluctuations may be expected throughout the year, restricting its use to certain locations.

Dry cooling technologies that are based on the use of air-cooled heat exchangers (ACHXs) offer the advantage of little to no consumption of freshwater, which may become critical in selecting heat rejection technology for certain regions. In some instances, the steam flow is sent directly through the ACHX-finned tubes (also known as air-cooled condensers, ACCs), whereas other designs are indirectly cooled, circulating a heat transfer fluid in a closed loop between the steam condenser and ACHXs. A comprehensive discussion of the advantages and disadvantages of ACHXs can be found in Refs. [9,15,17,18]. In short, the principal disadvantages are lower plant efficiencies because of the higher condensation temperatures, high turbine backpressures and increased heat rejection, all of which are linked by the on-site ambient conditions. These factors constitute a loss of power generation from approximately 2%–10% (or even higher) depending on the power plant technology and ambient temperatures [1,17]. High turbine backpressures require larger turbines that can work under such varying conditions.

Throughout the year, ambient temperature glide causes the ACC condensation pressures to range between 0.3 and 0.5 bar, whereas water-cooled technologies offer steady pressures from 0.07 to 0.1 bar. ACCs' wider range complicates the control and operation of power plants. The use of dry cooling technologies is usually constrained to locations with low ambient temperatures to reduce heat exchanger surface areas, whereas hybrid cooling systems (a combination of wet and dry technologies) are more common in locations with higher ambient temperatures.

Condensation temperatures must remain low to achieve higher thermal efficiencies, steadier condenser pressures and better control strategies of thermoelectric generation plants. One way to achieve such low temperatures with ACHXs is by integrating a thermally driven absorption refrigeration system (ARS) into the Rankine cycle of the power plant, operating in a closed loop configuration.

This paper investigates common Rankine cycle configurations for thermoelectric generation coupled with an ARS in the condenser loop to absorb the heat rejection requirements through its evaporator at design temperatures and thus "lift" its rejection sink temperature to a higher level where ACHXs are fit to operate. The ARS is driven by extracting (bleeding off) a portion of the steam that circulates through the steam turbine at the appropriate temperature that is required by the desorber (generator), studying the integration with single- and double-effect absorption chillers. The bleed mass fractions and system performance indicators are analyzed and discussed to maintain the power plant's functions at design condenser pressures and reduce the required water withdrawal and consumption of the system.

2. Cycle description

In this section, the description of the power plant configuration and its components are discussed, including common components in Rankine power cycles and absorption refrigeration cycles.

Fig. 1 shows a basic schematic of the system configuration that is proposed in this work. The interconnection of the steam condenser and the atmosphere is accomplished by means of an ARS, which offers the possibility to dissipate heat rejection at a higher temperature level and enable the use of ACHXs. The use of an absorption chiller is suitable for application because the chiller can be fired with steam that is bled off from the turbine with no additional heat input.

2.1. Rankine cycle

The Rankine cycle uses water as the working fluid, which is vaporized and used to power the turbine/generator units, where it expands, thus producing electricity. In its simplest form, this cycle has four main components: a boiler, steam turbine, condenser and feed-water pump. Superheating, reheating and regeneration are common modifications of this cycle to increase the system's thermal efficiency by raising the average steam temperature. Typically, one stage of reheating and multiple regeneration stages exist. The thermal efficiency of a power plant, η_{th}, is defined as the ratio of the

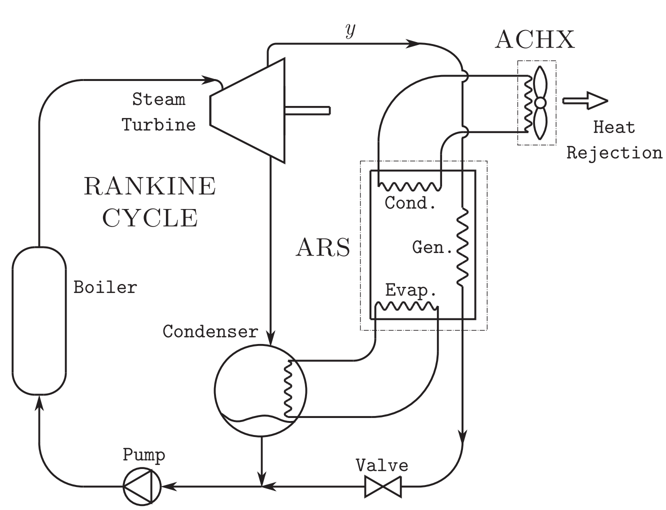

Fig. 1. Simple Rankine cycle configuration with an absorption refrigeration system that is coupled to the condenser. *y* represents the fraction of the total mass flow that is extracted to serve as heat input for the ARS system.

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