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Research paper

# Achieving near-water-cooled power plant performance with air-cooled condensers

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## HIGHLIGHTS

- Power plant condenser cooling accounts for 41% of US fresh water withdrawals.
- Power plants with air-cooled condensers (ACCs) suffer a 5–10% efficiency penalty.
- Simultaneous improvements to ACC heat transfer and pressure drop are needed.
- Emerging convection enhancement technologies could improve ACC performance.
- Hybrid wet-dry cooling improves ACC performance with minimal water consumption.

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## ABSTRACT

Power plants using air-cooled condensers suffer a 5–10% plant-level efficiency penalty compared to plants with once-through cooling systems or wet cooling towers. In this study, a model of a representative air-cooled condenser (ACC) system is developed to explore the potential to mitigate this penalty through techniques that reduce the air-side thermal resistance, and by raising the air mass flow rate. The ACC unit model is coupled to a representative baseload steam-cycle power plant model. It is found that water-cooled power-plant efficiency levels can be approached by using enhanced ACCs with a combination of significantly increased air flow rates (+68%), reduced air-side thermal resistances (−66%), and air-side pressure losses near conventional levels (+24%). Emerging heat-transfer enhancement technologies are evaluated for the potential to meet these performance objectives. The impact of ambient conditions on ACC operation is also examined, and two hybrid wet/dry cooling system technologies are explored to improve performance at high ambient temperatures. Results from this investigation provide guidance for the adoption and enhancement of air-cooled condensers in power plants.



## 1. Introduction

### 1.1. Water resources and the role of power plant condensers

Population growth and increasing energy intensity throughout much of the world are placing increasing strain on limited fresh water resources that are needed for residential use, power generation, industry, and agriculture. These factors and ecological considerations have led to increasing pressure on thermoelectric power generation utilities to reduce water withdrawals and consumption, even as demand for electricity increases. These conflicting demands are particularly difficult to satisfy because areas with the highest population growth, increasing water usage, and increased electricity demand coincide with areas with scarce water supplies [13,30,49]. Additionally, seasonal periods of peak power-generation demand often coincide with drought conditions.

Power plants currently account for 41% of US fresh water withdrawals [30], over 90% of which is employed for condenser cooling [17]. Historically, simple and low-cost water-to-steam once-through condensers were widely employed, and currently account for 43% of the US generation fleet. However, thermal pollution from the high return water temperatures (typically 10 °C above intake temperatures) and the water withdrawal rates required to achieve even such high return temperatures ($75–150\ m^3\ MWh^{-1}$, $1\ m^3\ MWh^{-1} = 0.26\ kgal\ MWh^{-1}$) have led to EPA restrictions on new construction [15]. Wet cooling towers represent an alternative condenser technology with comparatively

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**Nomenclature**

| | |
|---|---|
| $A$ | heat transfer area [$m^2$] |
| $A_{tot}$ | total air-side heat transfer area (tube and fins) [$m^2$] |
| $A_{tube}$ | tube outside heat transfer area [$m^2$] |
| $D_H$ | hydraulic diameter [m] |
| $h$ | convective heat transfer coefficient [W $m^{-2}$ $K^{-1}$] |
| $h_{eff}$ | effective heat transfer coefficient [W $m^{-2}$ $K^{-1}$] |
| ITD | initial temperature difference across condenser [°C] |
| $K_{dj}$ | jetting loss coefficient [−] |
| $K_{do}$ | downstream loss coefficient [−] |
| $K_o$ | outlet loss coefficient [−] |
| $K_{\theta t}$ | total loss coefficient [−] |
| $K_{up}$ | upstream loss coefficient [−] |
| $\dot{m}_{air}$ | air mass flow rate through air-cooled condenser cell [kg $s^{-1}$] |
| $\dot{m}_{steam}$ | steam mass flow rate through air-cooled condenser cell [kg $s^{-1}$] |
| $P$ | fan power consumption [W] |
| $P_s$ | heat-transfer-area specific fan power consumption [W $m^{-2}$] |
| $T_{air,in}$ | air inlet temperature to the condenser [°C] |
| $T_{air,out}$ | air outlet temperature from the condenser [°C] |
| $T_{amb}$ | ambient air temperature [°C] |
| $T_{steam,in}$ | steam inlet temperature to condenser [°C] |
| $U_s$ | heat-transfer-area specific volumetric air flow rate [m $s^{-1}$] |
| $V$ | volumetric flow rate [$m^3$ $s^{-1}$] |

low water withdrawal requirements (2–28 $m^3$ $MWh^{-1}$), and are currently installed in 42% of US thermoelectric power plants [11,30]. While thermal pollution of watersheds is a less significant concern for wet cooling tower installations, the increased water consumption through evaporation (2.3 $m^3$ $MWh^{-1}$ compared to 0.8 $m^3$ $MWh^{-1}$ in once through systems) may be untenable in areas with water availability concerns. Cooling ponds (14% of U.S. plants) also operate through evaporative cooling, and have similar water consumption rates. Although fresh water supplies can be conserved by increasing plant efficiency, recycling water supplies, using waste water, and other avenues, dry cooling systems have the potential to almost eliminate power plant water usage. Air-cooled condenser (ACC) technology is not yet widely employed in the U.S. (only in 1% of U.S. plants), but is expected to see increased adoption due to competing water demands and water conservation regulations.

### 1.2. Air-cooled condenser description

In the US, direct-coupled mechanical-draft air-cooled condensers have been utilized in all current dry cooling systems [16]. In these systems, steam exiting the turbine is routed to the air-cooled condenser through a series of large horizontal ducts running along the top of A-frame condensers. Each row of A-frame condensers consists of a number of cells. A single ACC cell has finned tubes arranged in parallel along the inclined walls of the A-frame unit. Many current ACC cell designs utilize a single row of finned tubes, with each tube consisting of a rectangular carbon steel channel with aluminum fins [16,33]. Steam enters the ACC cell through the large steam duct, condenses as it flows down the inclined tubes forming the walls of the A-frame, and is then collected in a condensate line at the bottom. A typical ACC cell has a footprint of 12 × 12 m, with finned tubes 9–12 m long and an apex angle of 60° [16,33]. Each finned tube has approximate dimensions of 25 × 190 mm, with 25 mm tall fins [16,55]. Air is driven through the tube banks and fins by large axial-flow fans approximately 9 m in diameter [16,33]. ACC condensers are generally placed 20–50 m above ground level, and are enclosed by wind walls to reduce the impact of wind and potential air recirculation [16,33]. Schematics of an ACC assembly, ACC cell, and an individual finned steam tube are presented in Fig. 1.

### 1.3. Air-cooled condenser challenges

Despite the reduced water usage in dry cooling systems, limited market penetration has been achieved in the US due to substantial tradeoffs in terms of cost and performance. Air-cooled condensers require substantially higher capital investment than wet-cooled condensers because they incorporate larger heat exchangers, have huge fin areas, and necessitate additional support structures [42]. Overall, installation and operational costs for ACC systems are currently 3.5–5 times as much as for wet cooling systems [1]. Typical levelized power production costs for plants with ACCs are \$3–6 $MWh^{-1}$ higher (up to ~15%) than for plants utilizing wet cooling [56]. However, expected increases in water usage costs could quickly eliminate this gap. Zhai and Rubin [56] estimated that increasing water costs from a baseline of \$0.26 $m^{-3}$ to \$1.64 $m^{-3}$ would result in equivalent costs, and Ref. [1] found that, depending on conditions, an increase in water cost to \$0.53 $m^{-3}$–\$1.06 $m^{-3}$ would be sufficient to eliminate this gap.

ACCs suffer a performance penalty relative to wet cooling systems due to the poor thermal transport properties of air, which is exacerbated by their greater relative performance degradation at elevated ambient temperatures. ACC air-side heat transfer coefficients (typically ~35 W $m^{-2}$ $K^{-1}$) are generally much lower than values for the water or evaporative-sides of wet cooled condensers. Air also has a much lower thermal capacity than water. At atmospheric pressure, air has a volumetric specific heat of 1.1 kJ $m^{-3}$ $K^{-1}$, while water has a specific heat of 4200 kJ $m^{-3}$ $K^{-1}$ and a latent heat of vaporization of 2,252,000 kJ $m^{-3}$. Thus, it is necessary to supply substantially more air than water to provide the same thermal capacity for heat removal from the condenser, which is accompanied by a large parasitic fan power requirement. Blanco-Marigorta et al. [6] found that with a steam condensation temperature of 37 °C, this results in an exergetic efficiency of just 26% for an air cooled condenser, compared to 63% for a wet condenser. This thermal capacity difference results in ACCs requiring a higher initial temperature difference ($ITD = T_{steam,in} - T_{air,in}$) than water cooling systems with cost-effective designs. Raising the ITD by increasing the steam condensation pressure results in a greater available air thermal capacity and increases the temperature difference driving the heat transfer process. However, this also results in increased steam turbine backpressure, and thus reduces the steam cycle efficiency and power output. Based on results from the present modeling effort, a 3 K increase in ITD leads to a 1.1% reduction in power generation. In order to match the advantages of plants cooled by wet condensers, the steam turbine backpressure must be reduced through the development of high performance and economical ACCs.

In addition to this performance penalty under design conditions, ACC performance can be sensitive to operating conditions, such as ambient temperature, wind, rain, hail, or solar radiation [33]. High ambient temperatures increase the steam condensation pressure, lowering the power plant output. Periods with high ambient temperatures typically coincide with peak electricity