Energy xxx (2014) 1–14

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Modelling the thermodynamic performance of a concentrated solar power plant with a novel modular air-cooled condenser

J. Moore [a,*], R. Grimes [a], E. Walsh [b], A. O'Donovan [a]

[a] Stokes Institute, Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Limerick, Ireland
[b] Osney Thermo-Fluids Laboratory, Department of Engineering Science, University of Oxford, Oxford, UK

A R T I C L E I N F O

*Article history:*
Received 20 October 2013
Received in revised form
1 March 2014
Accepted 6 March 2014
Available online xxx

*Keywords:*
Dry cooling
Air-cooled condenser
Air-cooled heat exchanger
CSP (Concentrated Solar Power) system analysis

A B S T R A C T

This paper aims at developing a novel air-cooled condenser for concentrated solar power plants. The condenser offers two significant advantages over the existing state-of-the-art. Firstly, it can be installed in a modular format where pre-assembled condenser modules reduce installation costs. Secondly, instead of using large fixed speed fans, smaller speed controlled fans are incorporated into the individual modules. This facility allows the operating point of the condenser to change and continuously maximise plant efficiency. A thorough experimental analysis was performed on a number of prototype condenser designs. This analysis investigated the validly and accuracy of correlations from literature in predicting the thermal and aerodynamic characteristics of different designs. These measurements were used to develop a thermodynamic model to predict the performance of a 50 MW CSP (Concentrated Solar Power) plant with various condenser designs installed. In order to compare different designs with respect to the specific plant capital cost, a techno-economic analysis was performed which identified the optimum size of each condenser. The results show that a single row plate finned tube design, a four row, and a two row circular finned tube design are all similar in terms of their techno-economic performance and offer significant savings over other designs.



## 1. Introduction

ACC's (Air-Cooled Condensers) can potentially reduce the water consumption of a power plant by up to 97% [1]. This is particularly significant for CSP (Concentrated Solar Power) plants which are typically located in extremely dry regions, where water for wet cooling systems is scarce. In many cases an air-cooled condenser may be the only feasible option for a CSP plant. However, the high operating costs and the corresponding hit on plant efficiency associated with an air-cooled condenser makes it an unpopular option and there is a clear requirement for a more efficient dry cooling system for CSP plants [1]. This is seen as a significant barrier to the development of CSP plants in many regions around the world. In Europe, the SET plan (Strategic Energy Technology Plan) [2] describes the potential for CSP to contribute 2.5% of the EU's energy by 2020. The SET plan directly highlights water availability in plant locations as a significant issue which must be addressed for CSP development. This paper is aimed towards the development of a novel air-cooled condenser which – compared to plants cooled by conventional ACCs – can potentially enhance CSP plant efficiency and reduce installation costs.

The current state of the art in air-cooled condensers consists of a series of rectangular plate finned tubes coupled with very large axial fans (approximately 10 m diameter), operated at a constant speed. These condensers have a number of inherent design issues. The fact that the fans usually operate at a constant speed means that most condensers continuously operate at one point only, and cannot adapt to an optimum operating point given the changing ambient conditions. Walsh et al. [3] highlighted some additional performance limitations of these condensers where they measured the air flow at the outlet of the tube bundle across one cell. The investigation showed that the heat removal is non-uniform across each cell and large regions of ineffectiveness are consistently present. The proposed condenser design considers the heat sink and fan array as a composite solution and employs much smaller (approximately 1 m diameter), speed controlled fans. Additionally, it is envisaged that the condenser and fan array be incorporated into a pre-assembled module and instead of erecting the very large existing ACC structures, that an array of smaller modules be installed. It is expected that this concept will offer significant installation cost savings. This paper particularly focuses on the air-side performance of the condenser as this is the dominant thermal

* Corresponding author.
*E-mail address:* james.moore@ul.ie (J. Moore).

http://dx.doi.org/10.1016/j.energy.2014.03.028
0360-5442/© 2014 Elsevier Ltd. All rights reserved.

**Nomenclature**

| | |
|---|---|
| $A$ | heat transfer area, m$^2$ |
| $A_{min}$ | free-flow area, m$^2$ |
| $C$ | cost, US$/€ |
| $Cc$ | capital cost, US$/€ |
| $C_{min}$ | minimum capacity rate, W/K |
| $D$ | fan diameter, m |
| $H$ | fin height (plate fins), m |
| $Kc$ | coefficient for sudden contraction |
| $Ke$ | coefficient for sudden expansion |
| $L$ | length of tube bank in flow direction, m |
| $M$ | mass, Kg |
| $N$ | fan speed, rpm |
| $P_{fans}$ | power, W |
| $Q$ | heat power, W |
| $S_d$ | diagonal pitch, m |
| $S_f$ | $1/n_f$ |
| $S_l$ | longitudinal pitch, m |
| $S_t$ | transverse pitch, m |
| $T$ | temperature, K |
| $U$ | overall thermal conductance, W/m$^2$ K |
| $W$ | plate fin tube width, m |
| $Z$ | fan to heat exchanger distance, m |
| $b$ | fin pitch (plate fins), m |
| $c_p$ | specific heat capacity, J/Kg K |
| $d_{ex}$ | tube exterior diameter, m |
| $d_{fin}$ | fin exterior diameter, m |
| $d_h$ | hydraulic diameter ($4 \times r_h$), m |
| $h$ | heat transfer coefficient, W/m$^2$ K |
| $h_{fg}$ | enthalpy of vaporisation, kJ/Kg |
| $k$ | thermal conductance, W/m K |
| $l$ | fin height (circular fins), m |
| $\dot{m}$ | mass flow rate, Kg/s |
| $n_f$ | number of fins per meter |
| $n_r$ | number of tube rows |
| $n_t$ | number of tubes per row |
| $p$ | pressure, Pa |
| $r$ | discount rate |
| $r_h$ | $A_{min}$ $L/A$, m |
| $r_j$ | specific tube row |
| $u_{max}$ | air velocity at minimum cross section, m/s |
| $x$ | duct depth (in flow direction), m |
| $f$ | friction factor |
| $Re$ | Reynolds number |
| $Nu$ | Nusselt number |
| $Pr$ | Prantdl number |
| $St$ | Stanton number |
| $\delta$ | fin thickness, m |
| $\varepsilon$ | effectiveness |
| $\eta_{surf}$ | surface effectiveness |
| $\mu$ | dynamic viscosity, Kg/m s |
| $\rho$ | air density, Kg/m$^3$ |
| $\sigma$ | ratio of free-flow to frontal area |

*Subscripts*

| | |
|---|---|
| $a$ | air |
| alum | aluminium |
| $c$ | Condensate |
| $f$ | Fin |
| $i$ | heat exchanger inlet |
| $m$ | mean |
| $o$ | heat exchager outlet |
| $t$ | year of operation |
| $s$ | steam |
| *steel* | steel |
| $\infty$ | ambient |

*Abbreviations*

| | |
|---|---|
| ACC | air cooled condenser |
| CSP | concentrated solar power |
| DNI | direct normal irradiance, kWh/m$^2$ |
| FD | forced draft |
| ID | induced draft |
| LCOE | levelised cost of electricity, €/kWh |
| MACC | modular air-cooled condenser |

resistance, particularly determining the appropriate balance between heat transfer and fan power consumption. A model was developed to investigate the effect of various design parameters on the performance of a 50 MW parabolic trough CSP plant.

A number finned tube designs were considered as possible heat exchanger surfaces and a series of tests were performed to determine their thermal and aerodynamic characteristics in order to model the effect of the condenser designs on power plant performance. The availability of different tube designs to manufacture full-scale prototypes in a realistic time frame constrained the options to a multi-row design consisting of a bank of circular finned tubes, or a single row of plate finned, elongated rectangular tubes, similar to those in many existing ACC designs. The initial prototype condenser module which was tested contained six rows of helically finned round tubes in a staggered, equilateral arrangement, like that shown in Fig. 1(a) and (b) and had a square face area of 4 m$^2$. As the air-flow through such a tube bank is chaotic, no simplified theory is available to predict heat transfer and friction characteristics. However, extensive experimental research has been performed on such designs and correlations exist to predict their performance. Many of these correlations [4–6] are only valid for a tube bundle with a minimum of four-six tube rows. Below four tube rows, vast changes occur in the flow field which affect turbulence levels and inlet and exit flow losses. The inlet and exit losses are due to a flow contraction at the heat exchanger core entrance and a flow expansion at the core exit. These effects are described in further detail in Kays and London [7]. Monheit [8] also describes flow losses which are inherent in an equilateral staggered tube arrangement due to the flow continuously accelerating and decelerating through the bank. Zukauskas [9] describes the effect of turbulence on the heat transfer in a tube bundle stating that the heat transfer in the inner tube rows may exceed by 30–70% that of the first row depending on the longitudinal pitch. In contrast to the circular finned tube design, the air-flow through the plate-finned tube design shown in Fig. 1(c) and (d) can be simplified to laminar rectangular duct flow, for which theoretical models exist to predict heat transfer and pressure drop. Flow through a duct comprises a developing region through a finite entrance length after which point the flow becomes fully developed throughout the remainder of the duct. The developing region occurs where the boundary layers over the duct walls are distinct and the core or free stream fluid does not experience the viscous presence of the walls [10]. In order to account for both regions a composite model must be employed. By applying an energy balance across the duct [11] and [12] have developed relationships to predict heat transfer and friction characteristics.

Please cite this article in press as: Moore J, et al., Modelling the thermodynamic performance of a concentrated solar power plant with a novel modular air-cooled condenser, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.03.028