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Balancing heat transfer fluid flow in solar fields

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Abstract

Proper distribution of heat transfer fluid in solar fields remains an issue for the concentrated solar power industry. Balancing fluid flow in solar fields is very challenging due to their complex piping networks. It is further exacerbated by the instantaneously and spatially varying solar radiation necessitating continuous flow adjustments to control heat transfer fluid temperature. Poorly balanced solar fields entail over and under heating of a fairly costly heat transfer fluid; thus, shortening its life span and the life span of equipment handling it due to frequent thermal shocks. Proper distribution of heat transfer fluid will eventually minimize equipment malfunction, maximize solar power generation, and improve operational safety. A flow control strategy aimed at properly distributing heat transfer fluid in solar fields has been developed along with a model for the proposed strategy. The strategy consists of manipulating solar field valve positions to control flow distribution and modulating pump speed to control flow rate in response to a continually varying solar radiation in order to attain a set temperature for heat transfer fluid exiting the solar field.

Keywords: Concentrated solar power; Parabolic trough collector; Heat transfer fluid; Solar field

1. Introduction

Parabolic trough collector (PTC) is the most economical and commercially available concentrating solar power (CSP) technology. PTC systems include numerous parabolic trough mirrors tracking the sun on a single axis. A heat transfer fluid (HTF) flows in the focal line of the troughs collecting solar heat that is transferred to high pressure water generating high pressure steam. The solar-generated steam is then used to propel a steam turbine connected to a generator producing electricity (Schindwoff et al., 1980).

A streamlined schematic of a generic PTC type CSP plant is shown in Fig. 1. The Plant includes two segregated loops: an HTF loop collecting solar heat in a solar field (SF) and a water loop receiving that collected solar heat to process it in a Rankine cycle power block (PB). The loops of a SF are structurally identical; therefore, HTF needs to be distributed equally among the loops to optimize solar energy collection during normal operating conditions. So, a manual control valve is typically placed at the entrance of each loop to manage the distribution of HTF among the loops of the SF.

HTF absorbs solar heat by flowing inside blackened pipes placed inside vacuumed envelops running in the focal line of the sun-tracking collectors. HTF exit temperature is controlled by manipulating its residence time in SF loops by adjusting its flow rate. Consequently, total HTF flow is determined by the speed of its circulation pump, whereas HTF loop flow is determined by pressure drop across the loop that can be adjusted by varying loop inlet valve position. A simplified SF layout of a PTC type CSP plant is shown in Fig. 2.

A robust heat exchanger train (HXT) made up of an economizer, an evaporator, and a super heater is connected

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Nomenclature

a	azimuth angle, radians
A	area, m^2
AT	altitude transverse, radians
AW	PTC aperture width, m
C	PTC mirror cleanliness, percent
Cv	valve flow coefficient
CSP	concentrating solar power
D	diameter, m
Day	day of year, day
DCS	distributed control system
DII	direct incident insolation, W/m^2
DNI	direct normal insolation, W/m^2
f	friction factor
FC	flow controller
FL	PTC focal length, m
FT	flow transmitter
G	generator
h	enthalpy, kJ/kg
HA	hour angle, radians
$Hour$	hour of day, h
HTF	heat transfer fluid
HXT	heat exchanger train
IA	incident angle, radians
IAM	incident angle modifier, percent
ℓ	longitude angle, degrees
L	length, m
m	mass flow rate, kg/s
n	counter
N	count
$NPSH$	net positive suction head, m
$Orientation$	PTC orientation angle, radians
P	pressure, bar
PB	Power block
PTC	parabolic trough collector
q	heat flow, W
RD	PTC row distance, m
Re	Reynolds number
S	speed, m/s
SA	shadow argument
SD	solar day, day
SF	solar field
SG	specific gravity
SH	solar hour, h
SP	set point
T	temperature, °C
TC	temperature controller
TC	time correction term, minute
$Tilt$	PTC tilt angle, radians
TT	temperature transmitter
TZ	time zone, h
U	overall heat transfer coefficient, W/m^2-°C
v	volumetric flow, m^3/s
VFD	variable frequency drive
VP	valve position
α	altitude angle, radians
δ	declination angle, radians
ε	pipe roughness, m
η	efficiency, percent
λ	latitude angle, radians
μ	viscosity, cP
ρ	density, kg/m^3

in series where water and HTF flow in a counter-current pattern. High pressure water enters the economizer to be heated to near saturation then evaporated to steam in the evaporator then turned into superheated steam in the super heater before it is forwarded to a steam turbine to generate power. Hot HTF coming from the SF flows through the HXT giving up its heat to the water loop to produce the desired high pressure steam before it is pumped back to the SF. An expansion vessel is placed before the HTF pump to accommodate extra HTF volume produced by its thermal expansion in the SF and to provide the necessary elevation head for the HTF pump to overcome its net positive suction head (NPSH).

Typically, SF header pipes resemble an H shape with loops branching out in opposite directions forming a geometrically symmetrical layout. The PB is usually placed in the middle of the SF to simplify HTF distribution, minimize pump load, and minimize the amount of HTF needed to fill the piping network. The PB zone includes the HTF expansion vessel, HTF circulation pump, HXT, and other auxiliary equipment as well as the Rankine cycle components such as the turbine, condenser, feedwater pump, deaerator, and others. A typical H-shaped SF layout of a PTC type CSP plant is shown in Fig. 3.

2. Background

A few researchers investigated the issue of HTF flow balance in solar fields for the purpose of controlling its outlet temperature. A computer simulation of HTF temperature control has been carried out by Schindwoff (Schindwoff et al., 1980) where strict control requirements were included in the control logic. A feedback control scheme was developed where a flow control valve was manipulated based on HTF temperature in each row of collectors. Another computer simulation of HTF temperature control via flow manipulation was set up by Zunft (Zunft, 1995) where the dynamics of a collector loop were modeled by a set of nonlinear first order hyperbolic partial differential equations. A feedforward controller was