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Real-time dynamic analysis for complete loop of direct steam generation solar trough collector

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ABSTRACT

Direct steam generation is a potential approach to further reduce the levelized electricity cost of solar trough. Dynamic modeling of the collector loop is essential for operation and control of direct steam generation solar trough. However, the dynamic behavior of fluid based on direct steam generation is complex because of the two-phase flow in the pipeline. In this work, a nonlinear distribution parameter model has been developed to model the dynamic behaviors of direct steam generation parabolic trough collector loops under either full or partial solar irradiance disturbance. Compared with available dynamic model, the proposed model possesses two advantages: (1) real-time local values of heat transfer coefficient and friction resistance coefficient, and (2) considering of the complete loop of collectors, including subcooled water region, two-phase flow region and superheated steam region. The proposed model has shown superior performance, particularly in case of sensitivity study of fluid parameters when the pipe is partially shaded. The proposed model has been validated using experimental data from Solar Thermal Energy Laboratory of University of New South Wales, with an outlet fluid temperature relative error of only 1.91%. The validation results show that: (1) The proposed model successfully outperforms two reference models in predicting the behavior of direct steam generation solar trough. (2) The model theoretically predicts that, during solar irradiance disturbance, the discontinuities of fluid physical property parameters and the moving back and forth of two-phase flow ending location are the reasons that result in the high-frequency chattering of outlet fluid flow. (3) The model validates that the solar irradiance disturbance at subcooled water region would generates larger fluctuation of fluid parameters than two-phase flow region or superheated steam region.

1. Introduction

Solar trough is a successfully commercialized Concentrated Solar Power (CSP) technologies, which has been rapidly growing at a considerable speed [1]. Solar trough use parabolic mirrors to concentrate the direct normal irradiation (DNI) to the absorber tube located along the focal line [2]. The tube fluid, mostly uses synthetic oil, is heated and flowed into a heat exchanger unit to generate steam up to 10 MPa at 370 °C. The hot steam is then used to produce electricity though a steam turbine [3]. To further reduce the levelized electricity cost, direct steam generation (DSG), in which water is directly heated in the absorber tube, has been proposed as a potential substitute to the oil-based technology [4]. DSG offers two major advantages over the oil-based technology: (1) lower investment costs [5], and (2) higher steam cycle efficiencies [6]. There is two-phase flow exists in the DSG pipelines. Therefore, the dynamic behavior of DSG-based fluid is more complex comparing to oil-based technology.

In recent years, the DSG technology has been validated in proof-of-concept projects such as the DIrect Solar Steam (DISS) project [7]. There are three common operating modes for DSG: (1) once-through mode, (2) recirculation mode, and (3) injection mode [8]. Once-through mode has a complete loop in collectors, including subcooled water region, two-phase flow region and superheated steam region [9]. Because of its simplicity, the once-through mode is generally considered as the most efficient and economical way of operation [10], but the most difficult to control [11]. Modeling the dynamic behavior of the pipeline process is essential to design,

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testing and validation of automatic control systems for DSG solar trough plant. Therefore, several models have been proposed in the literature to model the behaviors of DSG solar trough.

A non-linear dynamic model is proposed for DSG solar trough based on the Modelica language [12]. This model was confined to studying the recirculation mode, which had been selected as the solution for the first pre-commercial plant INDITEP. However, Simulations were performed considering only the boiler section, and the superheating section was replaced by an adequate pressure loss element [3].

Odeh et al. analyzed the thermodynamics characteristics of trough collector in Solar Electric Generating System (SEGS) [13], and have developed steady models for collector thermodynamics, heat loss [14] and transfer efficiency [15]. These models use collector wall temperature as an independent variable and are applicable to different working mediums.

Bonilla developed a dynamic simulator for DIrect Solar Steam (DISS) project. This dynamic simulator is based on a distributed-parameter model using the finite volume method [16]. The source of high-frequency chattering in the pipe model is studied and analyzed together with an approach to the problem which is based on the smooth interpolation of some thermodynamic properties [17]. This paper points out that the accuracy of this simulator needs improvements with better understanding of the physical origins of the high-frequency chattering issue.

Feldhoff et al. [18] proposed a discretized finite element model and a moving boundary model to analyze once-through DSG solar trough. The moving boundary model is a lumped parameter model combined with distributed information, which can be used for control studies and model based predictive controllers. The discretized finite element model is a distributed parameter model used for detailed system characteristics and understanding. In the discretized finite element model, the heat transfer coefficient in two-phase flow is assumed to be constant.

The production of solar trough plant depends on DNI, which is highly variable during cloudy period. Therefore, knowledge of the dynamic behavior of solar trough plant under the influence of cloud shading is particularly important. In this paper, a Nonlinear Distribution Parameter Model (NDPM) has been developed to model the dynamic behaviors of direct steam generation parabolic trough collector loops under either full or partial solar irradiance disturbance. Compared with the state-of-art models, the proposed NDPM possess two advantages: (1) adopting real time local values of heat transfer coefficient and friction resistance coefficient, and (2) considering the complete loop of collectors, including subcooled water region, two-phase flow region and superheated steam region. Therefore NDPM achieves more accurate modeling of dynamic characteristics of DSG collector loop during the period of DNI disturbance. This model is particularly useful to identify critical process conditions that may result in system failures.

2. Nonlinear distributed parameter dynamic model of DSG collector

As shown in Fig. 1a, solar irradiation is reflected by the concentrator onto the focal line where the absorber tube locates. The concentrated beams enter through glass tube wall and evacuated space, and exchange heat with water/steam inside the absorber tube. The necessary parameters to model the heat exchange process are shown in Fig. 1b.

The heat transferring process is modeled using the following assumptions:

(1) Uniform pipe diameter and wall thickness along the pipe length.
(2) Fluid in the pipe is assumed to be homogeneous on the radial direction.
(3) The thickness of the absorber tube is neglected.
(4) Heat transfer along circumference direction and on cross-section of fluid is not considered [19].
(5) Partial pressure drop of DSG collector due to valves, pipe joint, and other pipe-shape related factors is neglected.

2.1. Energy balance of the DSG collector

The solar irradiation received by the concentrator per unit length is

$$Q_1 = I_{\text{direct}} B \eta_{\text{opt}} K_{\tau\alpha} \tag{1}$$

where I_{direct} is the DNI, B is the width of concentrator aperture.

η_{opt} is the optical efficiency of DSG collector,

$$\eta_{\text{opt}} = \rho_{\text{r}} \tau \alpha \gamma \tag{2}$$

where ρ_{r} is the reflectivity of concentrator, $\tau\alpha$ is the transmittance–absorptance product caused by the absorptivity of absorber and transmittance of glass tube [20], γ is the intercept factor of collector [21].

$K_{\tau\alpha}$ is the incidence angle modifier,

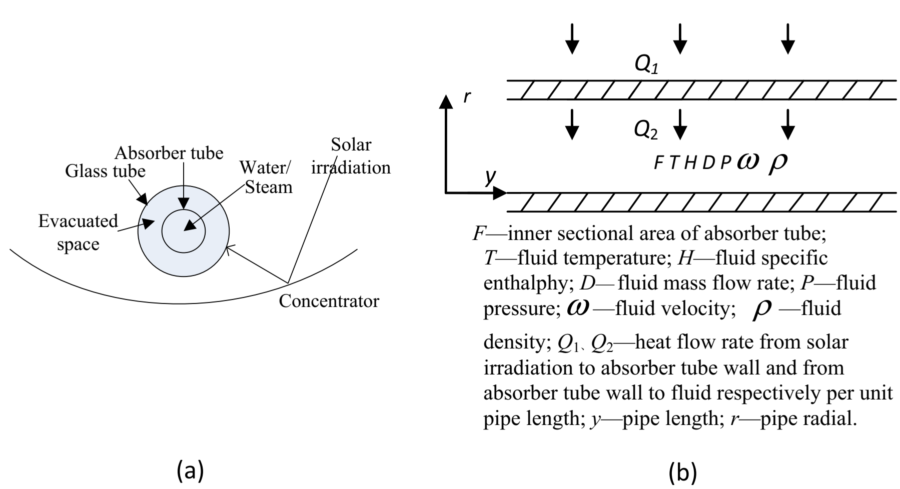

Fig. 1. Physical model of DSG collector (a) cross section of DSG collector; (b) longitudinal section of DSG collector.