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Regression methodology for sensitivity analysis of solar heating walls

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Abstract

Passive solar heating of buildings continues to be a great interest of renewable energy applications. Part of this interest focuses on solar heating walls. A solar heating wall (SHW) is a part of building walls that receive, store, and transfer solar thermal energy into the building. SHW sensitivity analysis is often performed to guide optimum designs. For the sensitivity analysis, the methodology used so far is numerical simulations. This work presents a new approach, regression analysis, and develops a general regression model. To show how to develop a specific model for a given SHW from the general one, how to do the regression, and how to validate the model, the lattice solar heating wall (LSHW) is selected as a case study. Detail heat transfer analysis is performed to develop the specific regression model for the LSHW sensitivity analysis. Four side-by-side test cells are constructed to obtain experimental data. The data are then used to determine the regression constants and coefficients and the time series numbers. Validation of the regression analysis shows that the model has very high confidence. The model is also used for LSHW optimization, yielding the same results as those from the simulation with the numerical simulation program, which further demonstrates that the proposed model is reliable.

Keywords: Regression; Solar heating wall; Sensitivity analysis

1. Introduction

Passive solar heating of buildings is a great interest of renewable energy applications. Part of this interest focuses on the thermal performance study of new materials and configurations of solar heating walls [1–5].

The solar heating wall (SHW) is a part of building walls that is designed to receive, store, and transfer solar thermal energy into the building. SHW examples are Trombe walls [6–8], phase-change-material solar walls [9,10], lattice solar walls [11], composite wall solar collectors [2], and honeycomb insulation walls [12,13].

Factors that influence SHW thermal performances can be classified as two categories: (a) design parameters, such as shading, orientation, insulation, glazing, wall configurations, and thermal properties, and (b) climate conditions, mainly solar radiation and ambient temperature.

To analyze the influence of design parameter changes on SHW thermal performances, sensitivity analysis is performed [14,15]. When analyzing the influence of a chosen design parameter on SHW thermal performances, the sensitivity analysis is performed by hour-by-hour calculations in a given climate pattern, allowing only this design parameter to change while keeping the rest constant.

To the author's best knowledge, methodology used so far for SHW sensitivity analysis is numerical simulations. Experimental measurements are only used to validate the simulation program.

Regression analysis, a powerful tool for solar energy applications [16–19], is scarcely used for SHW study. There are only two papers found out in the author's extensive literature search [20,21], and both of them are only for SHW thermal performance study.

The methodology of regression is especially useful for the study of new SHW materials and/or configurations where numerical solutions are not available in a period of time. The objectives of this study are: (a) to propose a general regression model for SHW sensitivity analysis; (b)

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Nomenclature

A_0	regression constant (bias)
a_j, b_k	regression coefficients
c_{lj}, d_{lk}	regression coefficients ($l = 1,2,3,4$)
D	hydraulic diameter of the LSHW vent
D'_h	the ratio of LSHW vent height to wall height
D_t	LSHW thickness
I	solar radiations
(i)	at time i
M, N	time series numbers to be determined by regression analysis
M_l, N_l	time series numbers to be determined by regression analysis ($l = 0,\ldots,4$)
Po	porosity of a lattice wall (vent section area to total wall area)
Q	solar heating wall heat gain
Q_{vc}	LSHW heat gain through vent air circulation
Q_{vr}	LSHW heat gain through vent radiation heat transfer
Q_{wc}	LSHW heat gain through inside surface convective heat transfer
Q_{wr}	LSHW heat gain through inside surface radiation heat transfer
T_a	ambient temperature
T_{lv}	LSHW vent surface temperature
T_{lw}	LSHW inside surface temperature
T_r	room temperature
T_v	average temperature of circulation air at the point leaving vent to room
T_w	average temperature of test cell inside surfaces, except for LSHW inside surface

to take the lattice solar heating wall (LSHW) as an example to show how to develop a specific model from the general one, how to arrange test matrix, and how to perform regression analysis; and (c) to validate the concretized model by comparing the predicted values with experimental measurements and those obtained from numerical simulation program.

2. A general regression model for SHW sensitivity analysis

Jiménez and Heras [20] and Kennish et al. [21] all assumed that the SHW is a linear system. The model Kennish et al. [21] proposed is, in the present symbols, of the form:

$$Q(i) = \sum_{j=0}^{M} a_j[T_a(i-j) - T_r(i-j)] + \sum_{k=0}^{N} b_k I(i-k) \tag{1}$$

This model cannot be used for SHW sensitivity analysis because all design parameters "hide" in regression constant regression coefficients a_j and b_k, and therefore cannot be seen. For SHW sensitivity analysis, the design parameters to be analyzed must appear in the regression equation.

The correctness of Eq. (1) is obvious from the theory of transfer function [22]. However, it is not practical even for SHW thermal performance study because its inputs include room temperature that is also an output needing to be determined.

From the point of view of heat transfer, a building system with SHWs can be approximated to a linear system. Consider this system as a "black-box" with multiple inputs and single output. The inputs are the solar radiation and ambient temperature, and the output is the room temperature. Accordingly, the room temperature is the linear superposition of the solar radiation and ambient temperature. Therefore, Eq. (1) can be rewritten as

$$Q(i) = A_0 + \sum_{j=0}^{M} a_j T_a(i-j) + \sum_{k=0}^{N} b_k I(i-k) \tag{2}$$

Eq. (2) applies when the following requirement meets:

(a) During experimental measurements, the room temperature is uncontrolled and there is no inner heating source; or
(b) During experimental measurements, the room temperature is controlled to a preset point, with little fluctuation.

Consider Z is a regression coefficient. It can be expressed as

$$Z = Z_0 + Z_1 f \tag{3}$$

where Z_0 and Z_1 are constants, and f is a function of the design parameters. Consequently, Eq. (2) can be rewritten as

$$Q(i) = A_0 + \sum_{j=0}^{M_0} a_j T_a(i-j) + \sum_{k=0}^{N_0} b_k I(i-k) + \sum_{j=0}^{M_1} f c_j T_a(i-j) + \sum_{k=0}^{N_1} f d_k I(i-k) \tag{4}$$

Eq. (4) is a general regression model for SHW sensitivity analysis. Function f can be determined with the following two approaches:

(a) Heat transfer analysis; and/or
(b) Multi-order approximation. For example, if x and y are two design parameters to be analyzed, the f may be assumed to be

$$f = a_1 x + a_2 x^2 + a_3 y + a_4 y^2 + a_5 xy + a_6 x^2 y + a_7 xy^2 + \cdots \tag{5}$$