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A comprehensive design and rating study of evaporative coolers and condensers. Part II. Sensitivity analysis

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Abstract

Sensitivity analysis can be used to identify important model parameters, in particular, normalized sensitivity coefficients; by allowing a one-on-one comparison. Regarding design of evaporative coolers, the sensitivity analysis shows that all sensitivities are unaffected by varying the mass flow ratio and that outlet process fluid temperature is the most important factor. In rating evaporative coolers, effectiveness is found to be most sensitive to the process fluid flow rate. Also, the process fluid outlet temperature is most sensitive to the process fluid inlet temperature. For evaporative condensers, the normalized sensitivity coefficient values indicate that the condensing temperature is the most sensitive parameter and that these are not affected by the value of the mass flow ratio. For evaporative condenser design, it was seen that, for a 53% increase in the inlet relative humidity, the normalized sensitivity of the surface area increased 1.8 times in value and, for a 15 °C increase in the condenser temperature, the sensitivity increased by 3.5 times. The performance study of evaporative condensers show that, for a 72% increase in the inlet relative humidity, the normalized sensitivity coefficient for effectiveness increased 2.4 times and, for a 15 °C increase in the condenser temperature, it doubled in value.

Keywords: Refrigeration; Air conditioning; Cooling tower; Evaporative condenser; Modelling; Research; Parameter

Etude approfondie et évaluation des tours de refroidissement et condenseurs évaporatifs. Partie II. Analyse de la sensibilité

Mots clés : Froid; Conditionnement d'air; Tour de refroidissement; Condenseur évaporatif; Modélisation; Recherche; Paramétre

1. On sensitivity analysis

Sensitivity analysis is a means to acquire insight about the importance of model parameters and, in turn, identify those, which are more responsive. Kitchell et al. [1] further explain that sensitivity analysis results are used to identify the most important model parameters, areas for future research, and the level of precision required for measuring system input variables. Masi et al. [2] clarified that, as a general rule, local methods require less extensive calculations, and provide a higher level of detail, whereas global methods may be best for handling large variations in the system parameters. In general, sensitivity analysis involves making changes to model rate coefficients singly or in

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Nomenclature

A	outside surface area of cooling tubes (m^2)
Le	Lewis number ($Le = h_c/h_D c_{p,a}$)
$\dot{m}$	mass flow rate of fluid (kg s^{-1})
m_{ratio}	water-to-air mass flow rate ratio ($m_{ratio} = \dot{m}_{w,in}/\dot{m}_a$)
NSC	normalized sensitivity coefficient
NTU	number of transfer units
NU	normalized uncertainty
SA	sensitivity analysis
t	temperature (°C)
U_Y	uncertainty in parameter Y, units of Y
U_{X_i}	uncertainty in parameter X_i, units of X_i
w.r.t.	with respect to
$\bar{X}$	nominal value of X, units of X
X_i	general input variable
Y	response parameter
$\bar{Y}$	nominal value of Y, units of Y
ε	effectiveness
$\in$	represents the perturbation value, units of X_i

Subscripts

a	air
ec	evaporative condenser
efc	evaporative fluid cooler
in	inlet
N	maximum number of independent variables
out	outlet
p	process fluid
r	refrigerant
wb	wet-bulb

combinations and determining the resulting changes in the model output [3]. In other words, sensitivities reflect the change rates (derivatives) of system responses with respect to design variables [4,5]. It should be noted that the aim of sensitivity analysis is to allow the comparison, on a common basis, of the role of different process parameters. The use of the normalized sensitivity coefficients, in particular, allows the direct comparison of parameters whose order of magnitude could be significantly different.

For instance, any independent variable X can be represented as

$$X = \bar{X} \pm U_X \tag{1}$$

where $\bar{X}$ denotes its nominal value and U_X its uncertainty about the nominal value. The $\pm U_X$ interval is defined as the band within which the true value of the variable X can be expected to lie with a certain level of confidence (typically 95%) [6]. In general, if a function $Y(X)$ represents an output parameter, then the uncertainty in Y due to an uncertainty in X can be expressed as

$$U_Y = \frac{dY}{dX} U_X \tag{2}$$

It is important to note that the uncertainty in a computed result could be estimated with good accuracy using a root-sum-square combination of the effects of each of the individual inputs. For a multivariable function $Y = Y(X_1, X_2, X_3 \ldots, X_N)$, the uncertainty in Y due to uncertainties in the independent variables is given by the root sum square product of the individual uncertainties computed to first order accuracy as [7,8]

$$U_Y = \left[\sum_{i=1}^{N} \left(\frac{\partial Y}{\partial X_i} U_{X_i} \right)^2 \right]^{1/2} \tag{3}$$

Physically, each partial derivative in the above equation represents the sensitivity of the parameter Y to small changes in the independent variable X_i. We note that the partial derivatives are typically defined as the sensitivity coefficients.

By normalizing the uncertainties in the response parameter Y and the various input variables by their respective nominal values, Eq. (3) can be written as

$$\left(\frac{U_Y}{\bar{Y}} \right) = \left\{ \sum_{i=1}^{N} \left[\left(\frac{\partial Y}{\bar{Y}} \frac{\bar{X}_i}{\partial X_i} \right) \left(\frac{U_{X_i}}{\bar{X}_i} \right) \right]^2 \right\}^{1/2} \tag{4}$$

The dimensionless terms in braces on the right hand side of the above equation represent the respective sensitivity coefficients and uncertainties in their normalized forms and are, therefore, referred to as normalized sensitivity coefficients (NSCs) and normalized uncertainties (NUs) [5]. Eq. (4) can, therefore, be written as

$$\left(\frac{U_Y}{\bar{Y}} \right) = \left\{ \sum_{i=1}^{N} \left[NSC_{X_i} NU_{X_i} \right] \right\}^{1/2} \tag{5}$$

Currently, only NSC is of interest to us. On replacing partial derivatives by ratios of discrete changes, the normalized sensitivity coefficients can be expressed as

$$\mathrm{NSC}_{X_i} = \left(\frac{\Delta Y_i}{\bar{Y}} \frac{\bar{X}_i}{\Delta X_i} \right)^2 \tag{6}$$

Since the sensitivity coefficients of the various input variables are normalized relative to the same nominal value $\bar{Y}$, a one-on-one comparison of the coefficients can be made thereby yielding a good estimate of the sensitivity of the result to each of the variables. Masi et al. [2] explained that the practical meaning of the normalized sensitivity coefficient is to establish how many order of magnitude of variation should be expected for the analyzed function when the considered parameter is altered by one order of magnitude. Obviously, a one order of magnitude alteration is usually not of practical interest, and it should be viewed