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Interaction effects between parameters in a vortex generator and louvered fin compact heat exchanger

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ABSTRACT

Heat exchangers for air conditioning applications are often of the fin and tube type. By choosing special fin geometries, the thermal performance of the heat exchanger can be enhanced. One of the recently proposed fin geometries for round tubes is the combination of louvers with a delta winglet vortex generator (VG). Several parameters impact the performance of this design, such as the louver angle and the angle of attack of the vortex generator. The fin geometry can be optimised by performing numerical simulations for different values of these parameters. Many authors use design of experiments techniques to reduce the number of simulations, such as the Taguchi method. However, this often implies the assumption that interaction effects between the parameters are negligible. In this work, a full factorial analysis is done to resolve all interaction effects. It is shown that there are important interactions between the height of the VG, the aspect ratio of the VG and the louver angle. These interactions are of the same order of magnitude as the main effect of the parameters and are therefore not negligible. Taking these interactions into account, the impact of the parameters on the heat transfer coefficient, the friction factor and the VG-1 performance evaluation criterion (PEC) are mapped. It is shown that the fin pitch is by far the most important parameter. Varying the louver angle, VG aspect ratio, the VG height ratio or the VG angle of attack results in a change of the VG-1 PEC of between 0% and 3.5%, depending on the interaction with other parameters.

1. Introduction

Finned round tube heat exchangers are used in many different industrial and residential applications. Using computational fluid dynamics (CFD) it has become feasible to evaluate the performance of many heat exchangers with different (fin) geometries. The louvered fin and the vortex generator fin are two geometries that have seen recent research interest. Because these geometries have a large number of geometric parameters, the amount of possible geometries to be evaluated using a full factorial sampling plan very quickly becomes too large.

For example, Hsieh and Jang [1] investigated a louvered fin and round tube heat exchanger and identified eight different geometric parameters. They decided that seven of these parameters were likely to exhibit quadratic behaviour in the range of interest, whereas for one variable two values were deemed sufficient to capture the effect. A full factorial sampling plan would then require $2^1 3^7 = 4374$ different geometries.

Especially if these geometries are to be evaluated at several Reynolds numbers, it is not feasible to perform this many CFD calculations within a reasonable timeframe with the available computational infrastructure. Furthermore, a full factorial analysis captures all interaction effects between all parameters. According to the sparsity of effects principle of Wu [2], interactions between three or more variables tend to be rare. A lot of the data is used to determine effects that are a priori expected to be insignificant. By making some additional assumptions on the interaction effects, design of experiments techniques allow performing the same analysis with much less data.

Using the L18 Taguchi orthogonal array, Hsieh and Jang [1] did their analysis using only 18 different geometries. This enormous reduction in amount of data required is due to the assumption that there are very limited interaction effects that is made in a classical Taguchi analysis. Because of the capability of treating a large number of parameters with very little data, several authors have used the Taguchi method to optimise fin geometries. For example, Yun and Lee [3] used the Taguchi method to optimise the slit fin geometry with respect to the JF criterion. They use 18 different geometries to investigate the behaviour of 7 geometrical parameters.

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Nomenclature

A_f	frontal area m^2
A_c	minimum free flow area m^2
A_s	heat transfer surface area m^2
c_p	specific heat capacity J kg^{-1} K^{-1}
D_c	tube diameter m
D_h	hydraulic diameter m
f	friction factor –
F_p	fin pitch m
h	heat transfer coefficient W m^{-2} K^{-1}
h	VG height m
h^*	VG height ratio $h^* = \frac{h}{s}$ –
j	modified Colburn j factor –
L	heat exchanger length m
L_p	louver pitch m
$\dot{m}$	mass flow rate kg s^{-1}
N	number of tube rows –
P	fan power W
P_l	longitudinal tube pitch m
P_t	transversal tube pitch m
Pr	Prandtl number –
$\Delta P_{friction}$	core friction pressure drop Pa
$\dot{Q}$	heat transfer rate W
Re	Reynolds number, $Re = \frac{v_c D_h \rho}{\mu}$ –
St	Stanton number –
T	temperature K
t_f	fin thickness m
u_c	core velocity m s^{-1}
u_f	inlet frontal velocity m s^{-1}
V	volume m^3

Greek symbols

ρ	density kg m^{-3}
η_o	surface efficiency –
σ	contraction ratio –
θ	louver angle °
μ	dynamic viscosity Pa s

Subscript

ref	a reference heat exchanger. Any heat exchanger under consideration has the same hydraulic diameter, mass flow rate, fluid temperatures and heat transfer rate

A fin geometry which has recently seen a lot of research interest is the vortex generator fin. Vortex generators are protrusions from the fin surface which generate longitudinal vortex structures. Fiebig [4] presented an extensive literature review and concluded that vortex generators could result in a global heat transfer enhancement of 50% for over 100 times the vortex generator area. Torii et al. [5] experimentally studied a vortex generator fin and round tube heat exchanger geometry, with different vortex generator parameters. For one specific positioning of the vortex generators, they found an enhancement of the heat transfer of 30% and a pressure drop reduction of 55%, for a Reynolds number of 350. For a different configuration, they found a heat transfer enhancement of 25% but accompanied with an increase in the pressure drop of 35%. This clearly illustrates that the vortex generator parameters are very critical to obtain a good performance of the vortex generator fin.

Several authors have attempted to find the optimal vortex generator geometry. He et al. [6] investigated different layouts and angles of attack of VGs to enhance an inline fin and round tube layout. For all cases, they found that both the pressure drop and the heat transfer coefficient increased as the angle of attack increased from 10° to 30°. Lemouedda et al. [7] used a Kriging surrogate model and a genetic algorithm to optimise the angle of attack of both an inline and a staggered layout of a fin and tube heat exchanger. The angle of attack was varied from −90° to 90° by rotating the VG around a vertical axis through its center. They found that the optimal angle of attack depended on the Reynolds number of the heat exchanger. Jang et al. [8] used the simplified conjugate gradient method to simultaneously optimise the transversal position and the angle of attack of a rectangular winglet vortex generator with respect to the VG-1 [9] criterion. They also found an increase in pressure drop and heat transfer coefficient as the angle of attack changed from 30° to 60°. The optimal angle depended on the Reynolds number.

By using the Taguchi method, Zeng et al. [10] were able to investigate the effect of eight different geometrical parameters. They varied the tube pitches and the fin pitch as well as vortex generator parameters such as the length, height and angle of attack. Using the JF factor introduced by Yun and Lee [11] as the PEC, they found that the vortex generator angle should be as large as possible and the height as small as possible within the considered limits. This result was independent of the Reynolds number.

Huisseune et al. [12] used the Taguchi method to analyse the performance of a compound combination of the louvered fin and vortex generators. Instead of considering the height and the length as parameters, they considered the ratio between the height and the fin pitch and the aspect ratio as vortex generator parameters. As opposed to Lemouedda et al. [7], they fixed the leading edge position of the vortex generator instead of the center.

Even though for the same number of evaluations the Taguchi method allows investigating many more geometrical parameters than e.g. the simplified conjugate gradient method or genetic algorithms, it remains an open question whether the fundamental assumption that interaction effects are negligible compared to the main effects of the variables is actually justified for a fin and tube heat exchanger or for vortex generator parameters.

In the current work, the interaction effects for the compound louvered fin and vortex generators case will be investigated. In order to understand the impact of interaction effects on the results of a Taguchi analysis, first a geometric interpretation of the Taguchi method is discussed. The concepts of parameter range, contribution ratio and interaction effects are introduced.

2. A geometric interpretation of the Taguchi contribution ratio

The results of a Taguchi analysis are often expressed as factorial effects or average results for each variable. These are obtained by taking the average over the results for all entries in the sampling plan where a certain variable has a certain level. This is elucidated by considering an example. Table 1 shows the L9 Taguchi array for four variables indicated by a letter from A to D, each having three levels. The corresponding results are indicated by the letter R.

The average result for variable C at level 1 is obtained by averaging the results for all entries where variable C is at level one, as shown by Eq. (1)

$$R_{C1} = \frac{1}{3}(R1 + R6 + R8) \tag{1}$$

The same process is followed to determine the result for every variable at every level. Once this is done, the optimal values for the