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PERFORMANCE SCREENING OF A LOUVERED FIN AND VORTEX GENERATOR COMBINATION

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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 optimized by performing numerical simulations for different values of these parameters. In this work steady state computational fluid dynamics simulations are performed for a fixed inlet frontal velocity. Many authors use design of experiments techniques to evaluate the performance with a small amount of simulations. However, this often results in the assumption that many interaction effects between the parameters are negligible. In this work, a full factorial analysis has been done which is able to resolve all interactions between all parameters. It is shown that there are important interactions between the height of the VG, the aspect ratio of the VG and the louver angle. Taking these interactions into account, the optimal values of the parameters are determined with the objective of maximizing the heat transfer coefficient.

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, even with CFD it is not feasible to investigate their performance using full factorial sampling plans.

For example, Hsieh and Jang [1] investigated a louvered fin and round tube heat exchanger and identified 8 different geometric parameters. They decided 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.

As these geometries must be evaluated at several Reynolds numbers, it is not feasible to perform this many CFD calculations within a reasonable timeframe. Furthermore, a full factorial analysis captures 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 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. The Taguchi method was also used among others by Zeng et al. [3] to optimise the vortex generator fin and by Huisseune et al. [4] to analyse the performance of a compound combination of the louvered fin and vortex generators. However, 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. This will be investigated in the current work for the compound heat exchanger considered by Huisseune et al.

NOMENCLATURE

j	[-]	Modified Colburn j factor: $\eta_o St Pr^{2/3}$
η_o	[-]	Surface efficiency
St	[-]	Stanton number $St = \frac{h}{\rho u_{in} c_p}$
h	[W/m²K]	Heat transfer coefficient

ρ	[kg/m³]	Density
u	[m/s]	X axis component of the flow velocity vector
c_p	[J/kgK]	Specific heat capacity on mass basis
Pr	[-]	Prandtl number $Pr = \frac{c_p \mu}{k}$
T	[K]	Temperature
μ	[Pa s]	Dynamic viscosity
k	[W/mK]	Thermal conductivity
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction
z	[m]	Cartesian axis direction
$\dot{Q}$	[W]	Heat transfer rate
$\dot{m}$	[kg/s]	Mass flow rate
A	[m²]	Heat transfer surface area
NTU	[-]	Number of transfer units
CR	[-]	Contribution ratio

Special characters

Δ		Difference or variable range in the Taguchi method
ϵ	[-]	Heat exchanger effectiveness
σ	[-]	Standard deviation

Subscripts

min	Minimum
max	Maximum
tube	At the tube wall
in	At the inlet of the computational domain

THE PHYSICAL MEANING 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 4 variables indicated by a letter from A to D, each having three levels. The corresponding results are indicated by the letter R.

Table 1 L9 Taguchi array

A	B	C	D	R
1	**1**	**1**	**1**	**R1**
1	2	2	2	R2
1	3	3	3	R3
2	1	2	3	R4
2	2	3	1	R5
2	**3**	**1**	**2**	**R6**
3	1	3	2	R7
3	**2**	**1**	**3**	**R8**
3	3	2	1	R9

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.

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

The same process is followed to determine the result for every variable at every level. Once this is done, the optimal values for the variables can be found. If there are no interaction effects, each variable can be optimised separately. For example, if the result needs to be as large as possible, then the level of each factor must be chosen so that the individual factorial effects are as large as possible.

Why this works is easily seen by fitting a polynomial model to the L9 sampling plan. The first level of a variable corresponds to a -1 value for the coordinate of the polynomial model, level 2 is assigned to 0 and level 3 corresponds to a coordinate of 1. The full polynomial model consists of 9 different terms.

$$f = a_0 + a_1 A + a_2 A^2 + b_1 B + b_2 B^2 + c_1 C + c_2 C^2 + d_1 D + d_2 D^2$$

This polynomial model represents a surface in a 5D space. A curve on this surface is obtained by fixing all variables except one to a certain value, and allowing this last variable to vary. This type of curve is called a parameter curve. For the variable C, the parameter curve takes the following form.

$$f = c_2 C^2 + c_1 C + constant$$

The constant term is independent of the value of C. Furthermore, due to the lack of interaction terms, the effect of the variable C does not depend on the values for the other variables. This implies that all parameter curves for the variable C are translated with respect to each other in the 5D space.

By introducing the sampling plan into the equation of the polynomial model, there are 9 equations to determine the 9 different coefficients. However, it is interesting to instead determine the results R1 to R9 as a function of the polynomial coefficients. These values are then substituted into the relations for the average results.

$$R_{C1} = c_2 - c_1 + \left(a_0 + \frac{2}{3}(a_2 + b_2 + d_2)\right)$$
$$R_{C2} = 0 \qquad + \left(a_0 + \frac{2}{3}(a_2 + b_2 + d_2)\right)$$
$$R_{C3} = c_2 + c_1 + \left(a_0 + \frac{2}{3}(a_2 + b_2 + d_2)\right)$$

Comparing these quantities to the equation of the parameter curve for C shows that the average factorial effects correspond to points on a parameter curve for C. Therefore picking the value corresponding to the largest average result, corresponds to evaluating a specific parameter curve for all the variable levels. This does indeed correspond to an optimisation of the variable level.

The relative importance of the variables is analysed by considering the range over which the average result varies. The ratio of the range of a single variable to the sum of the ranges of all variables is called the contribution ratio.

$$\Delta C = \max(R_{Ci}) - \min(R_{Ci})$$
$$CR_C = \frac{\Delta C}{\Delta A + \Delta B + \Delta C + \Delta D}$$

The polynomial model shows that this corresponds to the range over which a parameter curve varies for a given variable. Because of the lack of interaction effects, this result is the same for any parameter curve. This will no longer be true if interaction effects are present.

The impact of interaction effects will be investigated by calculating the range for every parameter curve which passes through one of the points in the sampling plan. If no interaction effects are present, these will all be equal. By reporting the average and the standard deviation over all parameter curves, the significance of the interaction effects is revealed. To the authors' knowledge, this idea has never been used in the heat exchanger literature.

GEOMETRY

The geometry of interest is shown in Figure 1. The fixed geometrical parameters are given in Table 2.

Table 2 Fixed geometrical parameters

Transversal tube pitch	P_t	17.6 mm
Longitudinal tube pitch	P_l	13.6 mm
Fin thickness	t_f	0.12 mm
Louver pitch	L_p	1.5 mm
Tube outer diameter	D_o	6.75mm
VG longitudinal position	ΔX	$0.5D_o$
VG transversal position	ΔY	$0.3D_o$

Table 3 Variables

Fin pitch	F_p	$1.4 - 1.8$ mm
Louver angle	θ	$22° - 35°$
VG angle of attack	α	$25° - 35°$
VG height ratio	h^*	$0.7 - 0.9$
VG aspect ratio	Λ	$1 - 1.5$

In the original study by Huisseune et al., the ranges were larger. The fin pitch was varied from 1.2 mm to 1.99 mm, the VG height ratio from 0.5 to 0.9 and the VG aspect ratio from 1 to 2. They used three levels for every variable and performed the analysis using a L9 Taguchi array to reduce the number of geometries from $3^5 = 243$ to 9. In this study a full factorial study will be used instead. In order to limit the number of calculations, two levels are used for every variable. In order to be able to capture the physics with only two levels, the range over which the variables are allowed to vary is reduced. The full factorial design requires the evaluation of $2^5 = 32$ different geometries, which is still feasible. The average computational time for a single case was 3 hours on two six core processors with 3.33 GHz CPUs

The 32 different geometries identified by the full factorial sampling plan are using CFD calculations with the commercial software Fluent. A fixed frontal velocity of 1.26 m/s is used to evaluate every geometry. This corresponds to a Reynolds number of 250 on the hydraulic diameter and the core velocity. Due to this low Reynolds number, a steady and laminar model is justified. Leu et al. [5] showed that for Reynolds numbers up to 780 a steady laminar model gives satisfactory results for a louvered fin and round tube geometry.

The computational domain is extended two tube diameters upstream of the heat exchanger, to take the flow contraction in this region into account. At the entrance of the computational domain, a uniform temperature and velocity profile is imposed. The inlet temperature is 20°C. Half of a periodic unit cell of the heat exchanger is analysed. Symmetric boundary conditions are used for the transversal boundaries of the domain. For the top and bottom of the domain, periodic boundary conditions are applied. Conjugate heat transfer simulations are performed where the conduction in the fin material is resolved. At the inner tube walls a uniform temperature of 50°C is imposed. At the interface between the fluid and solid domain, continuity of the temperature and the heat flux is imposed. Furthermore, the fluid velocity is equal to zero at the walls. The exit of the computational domain is located 10 tube diameters downstream of the heat exchanger exit. A constant pressure boundary condition is used at the exit of the computational domain.

The computational mesh used in this study is finer than in a previous study by Ameel et al. [6], for which the grid convergence index was determined to be 6% for the j factor for a frontal velocity of 2.6 m/s. For the same fixed geometrical parameters, the grid size in that study was 4 million cells, in this study the cell count is 6 million. Since the velocity in this study is 1.26 m/s instead of 2.6 m/s as in the previous study, the boundary layers are also thicker in this work. As a result the number of cells in the boundary layer is increased and the grid discretisation error is smaller. It is therefore possible to conclude that the grid used in this study results in a discretisation error which will be lower than 6%, without needing to do a separate grid convergence study.

In order to determine the modified Colburn j factor, the heat transfer coefficient must be determined. This is done by determining the number of transfer units from the effectiveness of the heat exchanger. Since the inner tube walls are held at a constant temperature, the effectiveness-NTU relation for one fluid with an infinite capacity rate is applicable.

Since the heat transfer surface area is known from the

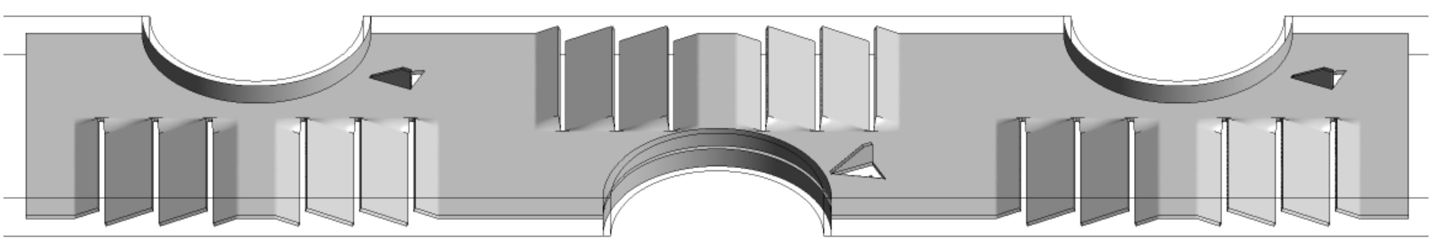

Figure 1 Compound fin geometry

NUMERICAL METHOD AND DATA REDUCTION

geometry and the mass flow rate and specific heat capacity are known input quantities, the product $\eta_o h$ can be determined once the effectiveness is known.

$$\epsilon = 1 - \exp\left(-\frac{\eta_0 h A}{c_p \dot{m}}\right)$$

The effectiveness for a single phase fluid with a constant heat capacity is equal to the dimensionless temperature at the outlet of the heat exchanger [7].

$$\epsilon = \frac{T_{fluid,out} - T_{fluid,in}}{T_{tube} - T_{fluid,in}}$$

The fluid outlet temperature is the adiabatic mixing cup temperature, which is obtained by integrating over the outlet of the computational domain.

$$T_{fluid,out} = \frac{\int \rho u T dA}{\dot{m}}$$

The modified Colburn j factor is then obtained from the product $\eta_o h$.

$$j = \frac{\eta_o h}{\rho u_{in} c_p} Pr^{2/3}$$

The Colburn j factor is now determined for every entry of the full factorial sampling plan. The j factors form the result column of a Taguchi analysis.

RESULTS

First the full polynomial model is fitted to all 32 data points. The variables are normalised so that the range of every variable is between -1 and 1. The coefficients are then already indicative of the relative importance of the different terms. For the sake of brevity, only eight terms with the largest (in absolute value) coefficients are shown, out of the total 32 terms.

$$j = 0.0356(1 - 0.03F_p + 0.019\theta + 0.011\Lambda + 0.0091h^* + 0.0046\alpha + 0.004h^*\Lambda + +0.00340\theta\Lambda + 0.00330\theta h^* + \cdots$$

This reveals that the sparsity of effects principle is valid for this case, as third order interactions are clearly less important than the main terms and the two variable interactions. The largest three variable interaction coefficient is 0.009, which is more than an order of magnitude smaller than most of the main variable effects. Nevertheless, these higher order interaction terms are not entirely negligible.

Furthermore, the effect of the vortex generator angle is of the same order of magnitude as several two variable interactions. In general, the interaction terms do not seem to be negligible. The coefficient of the interaction between the height ratio and the aspect ratio is of the same order of magnitude as the main variable effects.

Now that the full polynomial model is trained, the contour curves can be determined. Figure 2 shows the surface generated by fixing all parameters except for the height ratio and the aspect ratio at their minimal values. This generates two of the contour curves for the height ratio, which are indicated with the thick black lines. It is clear that these contour curves are not just translations of each other as assumed in the Taguchi methodology. Instead, the effect of the height ratio clearly depends on the aspect ratio. For low aspect ratios, the effect of the height ratio is very limited. In contrast, for the higher aspect ratio, the height ratio is important.

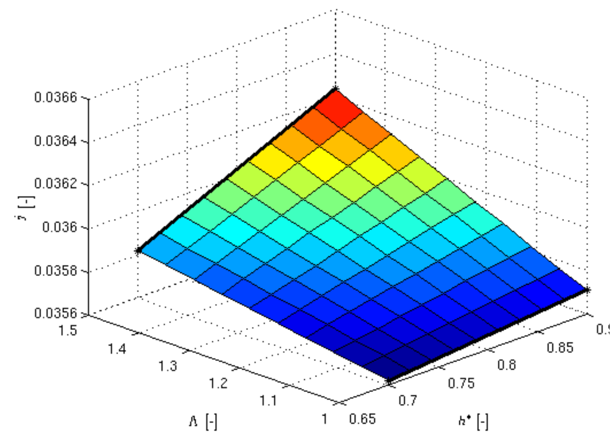

Figure 2 j factor as a function of $\boldsymbol{h^*}$ and $\boldsymbol{\Lambda}$ with all other parameters at the minimal value

The same thing is valid for the aspect ratio. If the height ratio is small, the effect of the aspect ratio is also quite limited. On the other hand, for the larger height ratio, the aspect ratio is seen to be very important. The physical reason for this can be found by investigating the flow itself.

Contours of the velocity magnitude 15% of the fin spacing above the fin surface are shown by Figure 3 for all four of the geometries corresponding to the corners of the $h^* - \Lambda$ space. It is clear that unless both the height ratio and the aspect ratio are both large, the vortex generator is located nearly entirely in the tube wake. In this case the vortex generator has almost no effect on the flow. As a result the j factor is also almost the same. It is only when both the height ratio and the aspect ratio are both large that the vortex generator protrudes out of the tube wakes. Only in this case does the vortex generator have a significant effect on the flow. This explains why the interaction between the height ratio and the aspect ratio is such an important interaction effect.

As the extent of the tube wakes around the vortex generator position is influenced by the louver angle, interaction effects between the louver angle and vortex generator parameters are also significant. The area of the vortex generator is determined by the three factor interaction of the height ratio, the aspect ratio and the fin pitch. This three factor interaction also determines the transversal distance between the tube center and the trailing edge of the vortex generator. For a given tube wake, this determines the extent to which the vortex generator protrudes outside of the tube wake. This explains why the third order interaction term is less than an order of magnitude smaller. The fourth order interaction term between this group and the louver angle physically represents the interaction between the trailing edge position and the tube wake extent and is also not negligible. The polynomial coefficient of this term is 0.002, which is also only an order of magnitude smaller than the largest terms. These are the only high order terms which are not negligibly small. Aliasing between these terms and other important terms must be avoided in the experimental design.

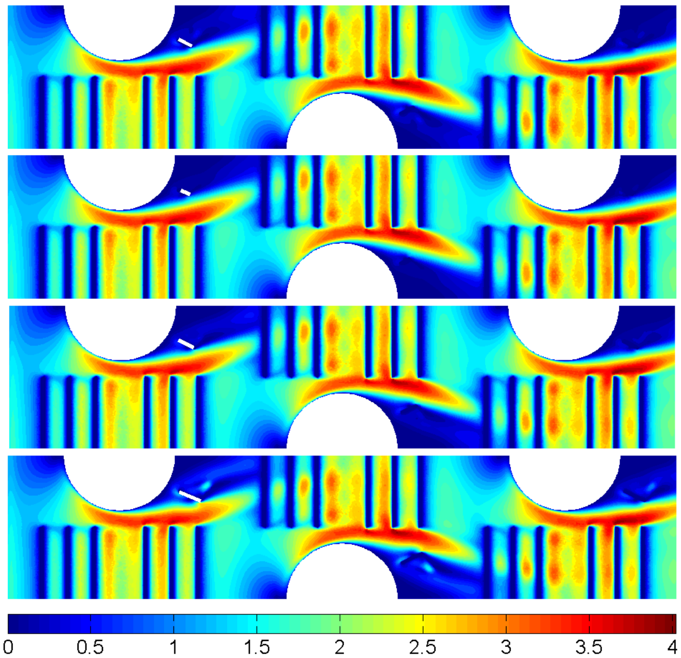

Figure 3 Velocity magnitude 15% of the fin spacing above the fin surface. Top to bottom: $\boldsymbol{h}^*$ large, both small, $\boldsymbol{\Lambda}$ large, both large.

The discussions of the polynomial model and of the flow clearly show that the interaction effects are important. The impact on the contribution ratios defined by Taguchi will now be investigated. For each variable there are $2^{5-1} = 16$ contour curves in total. The range over which a variable varies (Δ) is determined for each of these contour curves. The average range is determined for each variable. The sum of these average ranges is used to determine the contribution ratios. The standard deviation of the range over all the contour curves is also normalised by the sum of the average ranges. The result is shown in Table 4.

Table 4 Average and standard deviation of CR

Parameter	Range	Average CR	2σ CR
F_p	1.4 – 1.8 mm	32.8	9.2
θ	22 – 35°	19.1	24.1
α	25 – 35°	3.3	6.7
h^*	0.7 – 0.9	26.8	41.7
Λ	1 – 1.5	18	28.5

It is apparent that the standard deviation on the contribution ratio is largest for the louver angle θ, the height ratio h^* and the aspect ratio Λ. This indicates that the range over which the result (in this case the j factor) varies significantly between the different parameter curves. In other words, the behaviour of these variables is strongly influenced by the values of the other variables. These variables therefore show strong interaction effects with other parameters. This information can also be obtained from the coefficients of the polynomial model. It is these variables that appear in interaction terms with each other in the polynomial model.

The fin pitch shows a strong influence, the average contribution ratio is the largest of all variables. Additionally, the effect of the fin pitch depends less strongly on the values of the other variables. On the other hand, the vortex generator angle is seen to have a very small effect, without much interaction with other variables. This is in contrast with the findings of the original study, where varying the vortex generator over a range of 25-35° had a larger contribution than varying the louver angle over a range of 22-35°.

In a standard Taguchi analysis, these interaction effects are assumed not to exist. If in reality they are in fact present, the interaction effects are confounded with the main variable effect according to a complicated aliasing pattern. The extent to which the vortex generator protrudes from the tube wake has a very large effect on the performance of the louvered fin and vortex generator geometry. This is neglected by the Taguchi method.

CONCLUSION

Interaction effects are in fact present for the louvered fin and vortex generator geometry. The louver angle, the aspect ratio and the height ratio show interactions with each other that are of the same order of magnitude as the main effects.

Varying the fin pitch over a range from 1.4 to 1.8 mm, the louver angle from 22 to 35°, the height ratio from 0.7 to 0.9 and the aspect ratio from 1 to 1.5 all have the same order of magnitude effect on the modified Colburn j factor. Varying the vortex generator angle from 25 to 35° in contrast has an effect which is nearly an order of magnitude smaller.

The assumption of negligible interaction effects is not valid for the louvered fin and vortex generator geometry. Two variable interaction effects are important. In order to properly resolve the main variable effects, an experimental design which does not confound main factors with two variable interactions is required, such as a resolution IV fractional factorial design. For the purpose of optimisation of the fin geometry, the two variable interactions must also be resolved, requiring at least a resolution V fractional factorial design. If a Taguchi analysis is to be used, the aliasing structure must first be investigated to verify that the two variable interaction effects which are expected to be significant are not confounded with any main variable effects.

The sparsity of effects principle valid, as only two interactions between three and four variables were found to be significant. These significant interaction terms are not even a single order of magnitude smaller when compared to main and two variable effects. Design of experiments can still be used to reduce the amount of experiments, but it must be kept in mind that the accuracy of the results is limited due to the aliasing with the higher order terms. The interaction terms which are found to be significant can be explained on physical grounds. It is therefore a good idea in general to predict significant high order interaction effects based on intuition about the flow and make sure the experimental design does not confound these interactions with other important terms.

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