Review on the Comparative Study of Optimization Methods for Thermal Devices

Bopanna K D[#1], Abhishek Mamidi[#2], Akarsh R[#3], Neil George[#4], Yashas Bharadhwaj[#5]
[#1]Professor Mechanical engineering, New Horizon College of Engineering,[#2,3,4,5] Mechanical Engineering, New Horizon College of Engineering
Outer Ring Road, Near Marathalli, Bengaluru, Karnataka 560 103, INDIA

Abstract: *Various optimization methods were thoroughly studied, compared and reviewed for optimization of thermal devices. In this study, most commonly used optimization methods such as Full Factorial method, Partial Factorial method (Taguchi Method), Sequential Global Optimization method and Bottleneck methods are individually studied. Further, individual methods are reviewed on comparative parameters such as the number of trials, statistical reliability, complexity and the time taken to complete the given case study. On performing a comprehensive review of the above-said methods, it was concluded that Partial Factorial Method (Taguchi method) holds the precedence amongst the others.*

Key terms: *Optimization techniques, Full Factorial method, Partial factorial method, Taguchi method, Bottleneck method, Sequential Global Optimization method.*

I. INTRODUCTION

"Manufacturing is the backbone of any product development." On the contrary, industries have also been keen on the development of quality engineering with a minimized effort for their production. Thus arises the need for optimization. Optimization plays a key role from stages as early as the design of the end product to manufacturing the build concept. Optimization at each stage of the product development contributes tothe development of an optimized model. This paper deals with a comprehensive study on the various optimization techniques, envisioning the same for thermal applications. Few of the most commonly practiced optimization criteria such as Full Factorial method, Partial Factorial method (Taguchi method), Sequential Global optimization method and Bottleneck method of optimization has been taken into consideration. Here, the above-said methods are firstly studied in detail. A comparative study has been performed, which is discussed in this study at a later stage.

II. TYPES OF OPTIMIZATION TECHNIQUES

In modern day world, the ever-increasing demand for production has called for improved techniques for a modular approach to design in terms of optimized design, better build materials, efficient performance and extended product life. This draws the attention of the designers to continually cater the requirements of the industry.The optimization can be done by studying the various techniques available. Some of the available optimization techniques are Taguchi Method, Full Factorial Method, Sequential Global Optimization (SO), and Bottleneck Method

From the above description, selection of optimal design and selection of effective optimization is one of the primary challenges.

A. ***Taguchi Method***:"Taguchi Method also called as the partial factorial method is a statistical approach towards optimizing the considered system constraints and improve the eminence of product developed."[2] Initially all the tangible factors considered are classified into signal and noise parameters, of which the signal parameters are accounted. Further, an orthogonal array is employed to study the nature of various iterations to be performed. The Factors considered can range from geometrical parameters to physical or thermal parameters which impact the performance characteristics. Accordingly, a suitable orthogonal array is selected from the available standard set of arrays based on input parameters considered and their degrees of freedom. Suitable CAD model is developed on a convenient software interface. The analysis is performed on any of the solver workbench under the designated boundary conditions by importing the CAD model of the desired component incorporated with the array gradients. After conducting the experiments, ANOVA is carried out to compute the statistical data. Signal to Noise ratio is calculated and plotted. With the help of the obtained graphs and the parametric results from simulation, various iterative experiments are compared to find the most optimized variant.

B. ***Full Factorial Optimization Method:***“Full Factorial Optimization method is a technique for optimization of any designed thermal device that is conducted numerically.A full factorial analysis consists of conducting experiments taking into account all the possible combinations of the factors and their levels. [2] The flow and thermal fields for the protracted computational domain, including the thermal sink, are solved to determine the pressure descent and junction temperature distributions. Here, the fluid properties are assumed constant except for the density in terms of the momentum equation. The flow is considered to be steady, incompressible, and turbulent. The effects of viscosity and radiant heat are assumed to be negligibly small. Due to the symmetric geometry, the calculation is performed on only a quarter of the physical domain.” Using the assumptions stated above, the time-averaged governing equations for mass, momentum, and energy can be expressed in Cartesian tensor form as follows:

Continuity equation

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \quad (1)$$

Momentum equation

$$\frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho u_i' u_j'\right) + \rho g_i \quad (2)$$

Therefore, the results for the multi-objective function problem are obtained by using the following normalized equation in which the weighting coefficient (oi) is used:

$$\mathrm{F(X)} = \omega_1 \left[\frac{F_1(X)}{\Delta P^0}\right] + \omega_2 \left[\frac{F_2(X)}{\theta_{ja}^0}\right] \quad \omega_1 + \omega_2 = 1 \quad (3)$$

The importance of design variables is investigated before the design optimization is carried out. That is, the consequence of each design variable on the pressure drop and the thermal resistance is examined by varying only one variable among the baseline parameters.

C. ***Bottleneck Method:***“A Bottleneck is any resistance to the flow of heat in a thermal device. Calculation and presentation of a thermal bottleneck scalar field as acohesive part of a CFD simulation enables a practitioner to network with and understand the physical mechanisms by which heat is extracted from an electronics system. By applying the characteristics of this thermal bottleneck scalar to the thermal devicedesign aspects, one can identify near-optimal solutions with a minimal number of iterations.” [3]

.

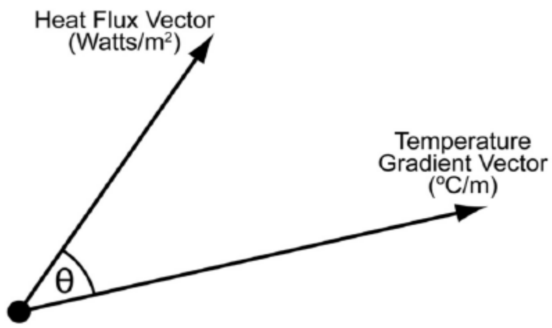

Fig.1:Vector diagram of heat flux (Watts/m²) and temperature gradient (°C/m)

This work details the principles of using thermal bottleneck concept to optimize the design and compare the results to that obtained by more traditional Design of Experiments (DOE) and numerical optimization techniques. Identification and conception of the BN scalar field offer insight into the physical mechanisms of how heat moves from source to ambient.

Large values of this Bottleneck numbers computed as a part of the thermal analysis, pinpoint areas of high heat flow experiencing thermal resistance (characterized by a large, aligned temperature gradient), and thus identify the thermal bottlenecks in a design. The maximum normalized scalar value in a model will provide an indication of the comparative levels of a thermal bottleneck in the simulated model.

If the temperature gradient is at right angle to the heat flux, then SC is simply the product of the vectors, since sin (90°) =1. Large values of the bottleneck pinpoint areas where large heat flux vectors are misaligned with large temperature gradient i.e., the heat is not moving directly toward a cooler area, and thus categorise locations where the heat transfer to the colder areas is significantly higher)and thus identify locations where the benefit in establishing a new heat transfer path to shortcut the heat to colder areas of the design is highest. Normalizing this scalar by the maximising value of a simulated model will provide a better opportunity foroptimization in a single simulated model.

D. ***Sequential Global Optimization Technique:***“This technique shows the optimization of the thermal device by the use of Computational Fluid Dynamics (CFD) and FLOTHERM. [4] The main benefits of using computerized design optimization are that better designs can be obtained.

TABLE I Comparison of various optimization techniques

Experiments/ Techniques / Criterion	Number of Experiments	Statistical Reliability	Complexity	Time Taken
Taguchi Method	Less	High	Complex (Can be reduced by using MINITAB)	Low
Bottleneck Method	Less	High	Highly complex	High
Sequential Global Optimization	High	Low	Highly complex (Framing surface response parameters)	High
Full Factorial	High	High	Complex	High

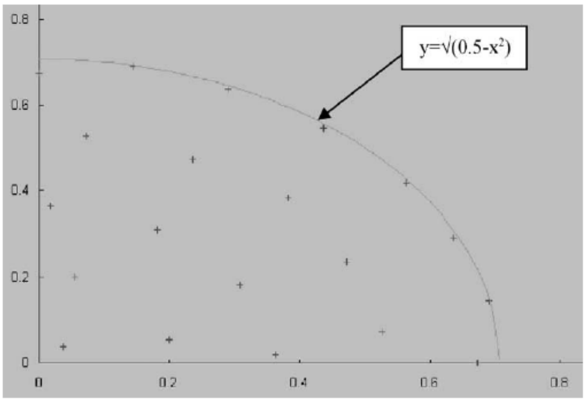

Fig 2: Design points within the *Trust Region*

The problem in this design optimization is to find a set of values for the design factors such that the design parameters satisfy certain constrictions, the response parameters satisfy certain constrictions, and some objective, being a function of the response parameters, is optimized. The possible existence of local minima makes it necessary to apply a global optimization strategy. First,an initial set of designs or *Design Points*are createdwithin the practicable space that will be run by the CFD tool. Local estimates of the CFD model outputs are obtained with the help of weighted regression techniques on a scaled design and response domain. It is warranted that the approximation is the current best design.“Theresulting compact models are then optimized within a *Trust Region* [4]pinpointed on the current best design to find the best feasible objective improving point which is a step toward the optimum design.” At each iteration, either a new design point is gauged (objective or geometry improving), or the trust region is reduced, depending on the progress of the optimization. The focus of the method is on getting good solutions with a limited number of iterativevaluations. The termination criteria for the conclusion are, the size of the trust region and the number of the iterative valuations performed to be minimum. Hence, the design optimization is achieved by improvements in the design using global optimization approach and the trust region approach making the technique very robust and reliable.

III. COMPARISON OF OPTIMIZATION TECHNIQUES

The range of optimization techniques available makes it a challenging task to choose the right technique. Each technique has its own advantages and disadvantages comparatively. The comparison can be made by selecting the most prominent criterions which are Number of experiments, Statistical reliability, Complexity and time taken, as described in Table I.

A. Comparison on a number of experiments shows that Taguchi method and Bottleneck method entails less number of iteration or repetitive experimental models in contrast to full factorial and Sequential global optimization method which has a requirement for a vast number of iterative experiments which includes all the possible permutations.

B. Comparison of statistical reliability based on data utilization and output shows that Taguchi method, Bottleneck method and Full factorial method has high reliability compared to Sequential global optimization method. This lack of statistical reliability of sequential global optimization method is due to its use of *Design points*and the *Trust region*to find the most optimised design.

C. Comparison on complexity reflects a level similar in all four types of optimization techniques. This complexity exists due to the use of permutations and complex numbers with vectors. The method of sequential global optimizationand Bottleneck have higher complexity due to the requisite of framing surface response parameters and identification of bottlenecks in the experimental models. The complexity in full factorial and Taguchi method can be reduced by the use of software's to form the arrays.

D. Comparison based on time-taken clearly justifies Taguchi method as the best as it removes the un-necessary iterations reducing the number of experiments hence reducing the time taken. The method of sequential global optimization, Bottleneck, and full factorial needs a sufficient dedication of time for the formation of design points, identification of trust region and Bottlenecks and in case of full factorial method its sheer number of iterative experiments.

IV. BENEFITS OF OPTIMIZING THERMAL DEVICE

1. Heat transfer rate can be increased without any preventivemaintenance.
2. An efficient way of increasing heat transfer coefficient.
3. The extended lifespan of the systemcomponents.
4. More organized temperature distributionprofile.
5. Reduces the system failure due tooverload.

V. REQUIREMENTS FOROPTIMIZATION

A. Taguchi Method:

1. Finding the tangible factors, then classify them into "signal and noise parameters."
2. Orthogonal array is employed to study the nature of various iterations to be performed.
3. Orthogonal array is selected based on the degrees of freedom and input parameters.
4. ANOVA is carried out to compute the statistical data. Signal to Noise ratio is calculated.
5. With the support of the obtained graphs and the parametric results from simulation, various iterative experiments are compared to find the most optimized variant.

B. Full Factorial OptimizationMethod:

1. It requires the pressure drop and junction temperature distributions by considering the flow and thermal fields which are in terms of mathematicalequations.
2. Flow properties are considered to be constant, except density in buoyancy terms of the momentum equation.
3. Viscous dissipation and radiation heat transfer are assumed to be negligiblysmall.
4. Time-averaged governing equations for mass, momentum, and energy are framed.

C. Bottleneck Method:

1. The thermal bottleneck scalar field is considered an integrated part of CFD simulation.
2. Understand the physical mechanisms by which heat is removed from a thermal system
3. Identification and visualization of the Bottleneck scalar field. How heat moves from source to ambient physically. Finding the SC number, considering heat flux and the temperature gradient

D. Sequential Global Optimization:

Requires "Computational fluid dynamics (CFD) tool, FLOTHERM", for the optimization Set of values for the design parameters and Response parameters Defining the Design Points within the feasible space called trust region that will be run by the CFD tool.

At each iteration, a new local linear approximation is built and the trust region reduces as the design approached its optimized form.

VI. ADVANTAGES AND DISADVANTAGES OF VARIOUS METHODS

A. Taguchi Method:

1. Number of iterations is less compared to othermethods. It is majorly reduced by the creation of an orthogonal array.
2. The results obtained are highly reliable.
3. The complexity of this method is high but it can be reduced by using Minitab software
4. The time required for the optimum result is very less.

B. Bottleneck Method:

1. The number of experimentation is less compared to other optimization methods.
2. Statistical reliability of the results obtained are high
3. The complexity of solving the vectors and respective mathematical equations is high thereby increasing the complexity of optimization technique.
4. The Time invested to solve the equation is really high.

C. Sequential Global Optimization:

1. The Number of iterations is high compared to other methods of optimization.
2. The statistical reliability of the results obtained is low. The complexity of the

framing surface response parameters is high, thereby increasing the overall intricacy.

3. The time taken for performing this optimization method is high.

D. Full Factorial Method:

1. The number of experimental iterations is comparatively high with respect to other methods.
2. The statistical reliability of this method is high.
3. The complexity of solving for all iterations in full Factorial equation is a tedious job thereby making it complex.
4. Solving equations not only increases the complexity, also increases the time taken for performing the iterations.

VII. CONCLUSION

In this study, various methods of optimization were reviewed, of which Taguchi Method also referred to as the partial factorial method was more likely considerable for the reduced number of iterations and overall time consumed despite the higher statistical reliability. The other techniques, though it holds precedence amongst the existing optimization methods, proves to be multifarious either in the number of iterations, their statistical reliability, complexity or the time taken to compute the optimized results. Hence, it can be concluded that the Taguchi Method is a more reliable Optimization model being an economical and cognizant technique.

REFERENCES

[1] Hong-Sen Kou, Ji-Jen Lee & Chi-Yuan Lai (2003) Thermal Analysis and Optimum Fin Length of a Heat Sink, Heat Transfer Engineering, 24:2, 18-29, DOI: 10.1080/01457630304083

[2] Srinivas Athreya, Dr. Y.D.Venkatesh, Application Of Taguchi Method For Optimization Of Process Parameters In Improving The Surface Roughness Of Lathe Facing Operation, International Refereed Journal of Engineering and Science (IRJES), Volume 1, Issue 3 (November 2012), PP.13-19

[3] Robin Bornoff, Byron Blackmore & John Parry, Heat Sink Design Optimization Using the Thermal Bottleneck Concept, 27th IEEE SEMI-THERM Symposium, 978-1-61284-736-8/11/$26.00 ©2011 IEEE.

[4] John Parry, Simulation-Based Design Optimization Methodologies Applied to CFD, IEEE transactions on components and packaging technologies, vol. 27, no. 2, June 2004