

# Sizing of Coolant Passages in an IC Engine Using a Design of Experiments Approach

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## ABSTRACT

Determining coolant flow distribution in a topologically complex flow path for efficient heat rejection from the critical regions of the engine is a challenge. However, with the established computational methodology, thermal response of an engine (via conjugate heat transfer) can be accurately predicted [1, 2] and improved upon via Design of Experiment (DOE) study in a relatively short timeframe. This paper describes a method to effectively distribute the coolant flow in the engine coolant cavities and evenly remove the heat from various components using a novel technique of optimization based on an approximation model. The current methodology involves the usage of a sampling technique to screen the design space and generate the simulation matrix. Isight, a process automation and design exploration software, is used to set the framework of this study with the engine thermal simulation setup done in the CFD solver, STAR-CCM+. This is followed by the construction of a approximation model which aids in evaluating the interaction between the design variables (coolant passage dimensions). The methodology utilized here enables the prediction of the thermal map of the engine in the early stages of design and minimizes the need for expensive hardware testing, thus reducing the product development cycle time and cost.

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## INTRODUCTION

New fuel economy regulations have pushed engine designs toward obtaining higher power density. As a result, there is more heat generation in the combustion chamber, leading to higher thermal load for an IC engine. Thermal load combined with mechanical load affects the structural integrity of an IC engine. Therefore, a robust engine design, by definition, should be able to sustain the aforementioned loads and maintain its structural stability. In order to keep the metal within the acceptable temperature limits under high thermal loads, efficient and timely heat removal from the engine is critical.

An efficient heat exchanger requires larger surface area and greater coolant flow rate for enhanced rates of heat rejection. An IC engine, however, offers multiple constraints and poses great challenge on the rate of heat removal due to its inherently complex topology. Engine performance and durability are strongly influenced by the efficiency of the heat removal. Inadequate removal of heat will result in locally high temperature zones, which could initiate undesirable phenomenon such as knocking. The resulting high temperatures could also cause structural failures including distortion and cracking. Similarly, excessive cooling could potentially reduce the efficiency of the engine by creating low temperature zones, which will impede complete combustion and increase unburnt hydrocarbons emissions.

Typically, heat is rejected from an IC engine via engine coolant flowing near the combustion chamber and the surrounding region. The engine coolant volume is called the coolant jacket, and is

topologically the most complex path in the coolant loop. The challenge here is to achieve the optimum coolant flow distribution across the water jacket to obtain the desired temperature distribution of the metal, and minimize pressure drop in the water jacket. This requires a large number of design iterations. As compared to laborious and expensive physical testing and the instrumentation costs, numerical analysis of the cooling system using computational fluid dynamics (CFD) is a cost effective way of optimizing the coolant flow path of an engine.

Conjugate Heat Transfer (CHT) analysis is best suited to obtain the engine metal temperature distribution under steady thermal load. In CHT analysis, the thermal field of the entire system is predicted by solving fluid and solid computational domains simultaneously. The temperature field at the fluid-solid interface is computed through thermal coupling of the two domains. Recently in the automotive industry CHT analysis has widely been used to predict the temperature map across the engine [1, 2, 3, 4, 5, 6].

Because of the faster turnaround time, CHT opens a gateway for improving the performance of coolant jackets [7]. The optimization of engine coolant jacket is a multi-objective study aimed at effectively removing heat and minimizing the pressure drop of the coolant across the engine while maintaining the peak metal temperatures within acceptable limit. Lowering peak temperatures help in increasing the fatigue safety factors. Additionally, low cylinder to cylinder peak temperature variation prevents unwanted

phenomenon such as engine knocking. Minimizing the pressure drop across the engine allows the water pump to require less input power, resulting in improved fuel economy. The magnitude of the optimization problem depends on the number of design parameters and levels of variation for each parameter. In general, optimization of the coolant jacket is a computationally intensive and challenging task.

A baseline analysis is performed on nominal size of all the design parameters. Based on the temperature distribution of the baseline configuration, areas of concern and improvement are identified. These identifiers, usually known as the “design parameters”, are the focus of a DOE and/or optimization study. Ideally, in order to understand the behavior of these design parameters on the system, a full factorial analysis, which evaluates all the parameters at all different levels, is to be performed. This is feasible for a system with a small number of design parameters and variation levels. For a system where the number of design parameters is large, this method is rendered impractical. To eliminate the need for CHT evaluations over the entire design space, sampling techniques are used which efficiently screen large design spaces. The sampling technique should be capable of representing the entire design space with the least number of sample points, while avoiding any unexplored region. The study by Barros et al. [8] evaluates various sampling techniques and their effect on the approximation model. The study concludes that space filling techniques such as Sphere packing design or Latin Hypercube perform well, especially when the optimized solution is assumed to be in the interior of the design space.

Once the combination of the various design parameters, known as the design matrix is generated, desired outputs known as design responses are computed in a CFD code. This set of output data is used to establish a mathematical model which characterizes the relation between the design parameters and design responses, known as an approximation model. Approximation models are used as surrogates for the actual computational models. They explore inherently complex and unknown relationships between the design parameters and design responses. This data is used to predict the design responses for parameter combinations that are not a part of the design matrix.

Following the generation of an appropriate approximation model, the final task is formulating the design problem and finding the optimized solution. Typically, optimization of any system involves reducing the entire problem to a mathematical form known as an “objective function” and solving either for minimizing or maximizing the value of this function within the constraints. There are various techniques available for achieving an optimal solution. These include, but are not limited to, direct search methods using the actual function value, gradient methods involving first or higher order derivatives, and the more recent Genetic Algorithm methods. Each of these techniques differs in terms of formulation and its success in finding an optimized solution greatly depends upon the definition of the problem. Typically, direct search and gradient methods predict local optima whereas Genetic Algorithms tend towards predicting global optima.

Due to the complex and unique nature of each problem, it is important to note that there is no single technique available for solving all optimization problems efficiently. The technique that

works for each problem is purely based on the physics of the problem, the design parameters, constraints, and the problem formulation itself. Therefore, it is crucial to investigate different available techniques and identify the one best suited for a particular problem. In addition, a combination of the multiple techniques may have to be used to make the process effective [9].

Multi-Response optimization based on an approximation model is documented by Liu and Jiang [10], using a DOE based approach. DOE and optimization techniques have been increasingly used in automotive industry in the past few years for various computational design problems involving vehicle as a whole [11, 12] as well as engine components [13, 14, 15, 16]. These tools have enabled the design of various engine components in the early stages of development using a computational model resulting in less experimental testing. Based on the available resources and the well-established CHT methodology, the possibilities of improving the coolant jacket are tremendous. However, due to the complex geometry of coolant jacket, only critical regions are optimized. One of the engine features considered critical for coolant flow distribution across the engine are the coolant transfer holes in cylinder head gaskets.

The current methodology entails multiple tasks, starting with strategic sampling of the design space using Design of Experiments (DOE), characterizing the selected sample by building an approximation model and the use of various optimization routines to mathematically formulate the problem and search for the optimized solution. At the end, the optimized design generated is validated by the CFD simulation. This study focusses on optimizing the coolant transfer holes in the cylinder head gasket using the Design of Experiment approach. StarCCM+, CFD simulation software by CD-Adapco, is used for performing the conjugate heat transfer analysis and Isight, optimization software by Dassault Systems, is used as an automation and optimization tool. Optimal Latin Hypercube is used to sample the design space and the Radial basis functions are used to build the approximation model. Finally gradient based optimization techniques are implemented to search through the design space for the optimum solution.

The methodology discussed in this paper is a novel approach to optimize engine coolant jackets based on an approximation model as opposed to numerically solving a few pre-determined designs in a CFD code [7]. The approximation model enables the analysis of multiple designs mathematically, leading to reduced turnaround time for engine coolant jackets design.

## COMPUTATIONAL DOMAIN

The computational domain used for DOE-optimization consists of engine block, head gasket, cylinder head along with intake and exhaust valves, valve guides, and valve seats. The intake and exhaust valves are modeled at their closed position to establish the heat conduction from the valves to cylinder head. [Figure 1](#) shows the computational domain including all the afore-mentioned components. The fluid domain is shown separately in [figure 2](#). Conjugate heat

transfer analysis is carried out for the engine solid and coolant. The details of model building, choice of physics continuum, and solution algorithm are discussed in the studies by Iqbal et al. [1, 2]

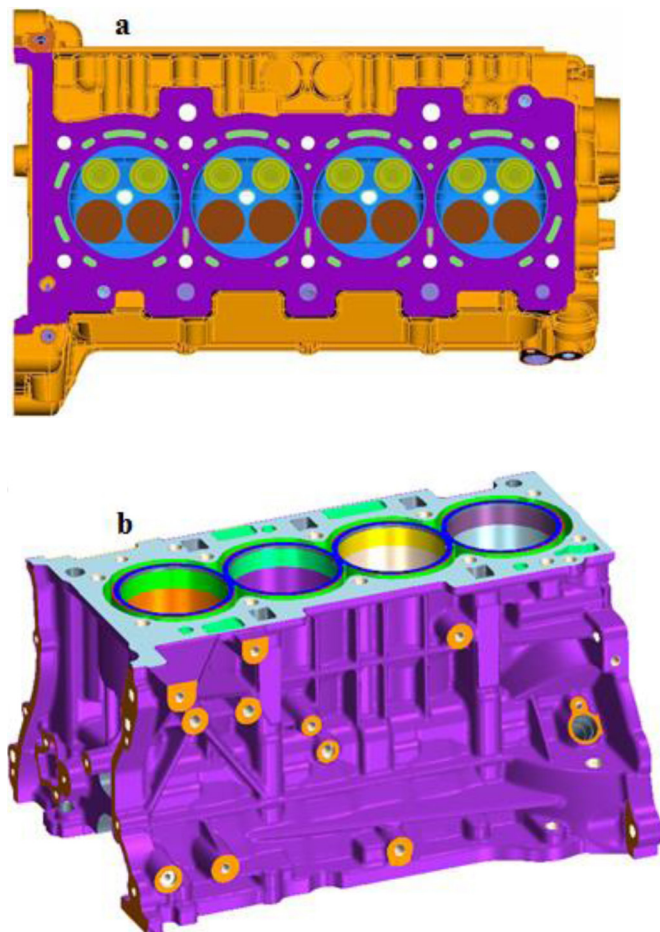


Figure 1. Computational domain; (a) Cylinder head; (b) Engine block

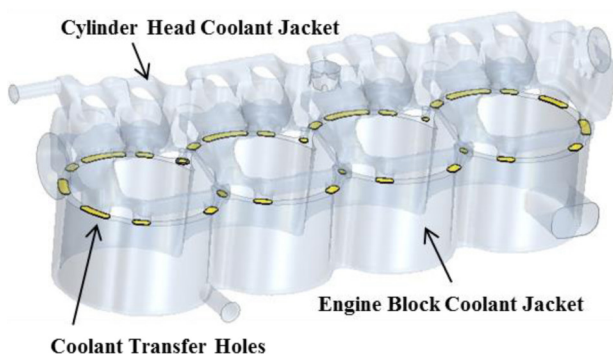


Figure 2. Fluid domain

## DOE - OPTIMIZATION APPROACH

The design of experiments followed by approximation and optimization is built on an established baseline model. The current study is aimed at optimizing the coolant transfer holes using CHT analysis. Therefore, as a first step, CHT model of an engine is prepared according to the methodology documented in the studies by Iqbal et al. [1, 2]. Once the baseline CHT model is simulated and

analyzed, the design parameters are identified. In the current study, the cross sectional area of coolant transfer holes in the head gasket are chosen as the design parameters. The bounds of each of the metering holes have been identified based on the manufacturing feasibility

Figures 3 and 4 shows outputs in cylinder head and engine block used as constraints. Each of the outputs have a set peak temperature limit, based on the material. The maximum velocities attained by the coolant have to be within set limits to prevent erosion of the material. The cylinder to cylinder variation in peak temperatures has to be within a certain range to mitigate phenomenon such as bore distortion in the engine block and localized hot zones in the cylinder head. Finally, the peak temperatures at the metal coolant interface have to be below the coolant temperature at which film boiling initiates at the specified system pressure.

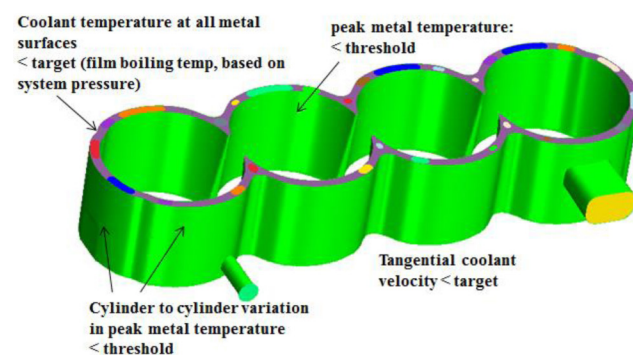


Figure 3. Design targets in block coolant jacket

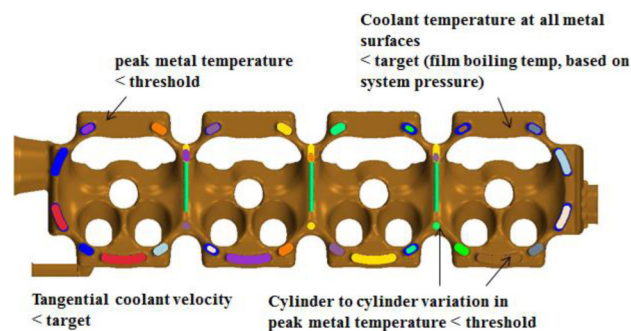


Figure 4. Design targets in head coolant jacket

## Design of Experiments

With the baseline analysis established, design parameters defined, and constraints set, the matrix of test points is determined next. This is also termed as an experimental design which is defined by Montgomery as a “test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for change in the output responses [17].” The “purposeful changes” referred above are the changes on a set of independent design parameters. Ideally, in order to gain insight into the behavior of a system, all the independent variables should be varied at each level, known as full factorials experiments. While this approach works for small scale systems, analyzing a large scale system with multiple non-discrete parameters is impractical because of the exorbitant time required to complete the analysis. There are numerous techniques available in the literature for sample design.