Automatic Spray Pattern Designs using Isight

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Abstract: The spray pattern of the gasoline direct-injection (GDI) multi-hole injector plays critical role with respect to the fuel economy, engine performance and emission characteristics in the spark-ignition direct-injection engines (SIDI). Manually matching the correct spray pattern with the combustion system can be a very time-consuming, trial-and-error process due to the complicated in-cylinder charge-spray interactions and the broad selection of engine load-speed conditions. Automated spray pattern designs could expedite the combustion system development process and reduce the work load of the engine analyst.

In this study, the optimization software, Isight is coupled with current state-of-the-art computational fluid dynamics (CFD) simulations of in-cylinder mixture preparation to automate the spray pattern optimization for an engine combustion system. The spray pattern is automatically adjusted to minimize the fuel vapor stratification and liquid wall wetting in the cylinder at three different operating conditions. Mixing homogeneity has been achieved by using the optimized spray pattern. No significant increase of wall wetting is observed.

Keywords*: Isight, Optimization, Star-cd, Spray Pattern, GDI multi-hole Injector, In-cylinder Mixture Preparation.*

1. Introduction

In order to meet more stringent government regulations for emissions and fuel efficiency, direct injection becomes one of the major methods along with high compression ratios and turbocharging to improve engine performance and fuel economy. In the homogeneous-charged spark ignition direct injection (SIDI) gasoline engine, the fuel is directly injected into the cylinder, it is very critical to achieve homogenous mixing of fuel vapor and air with less wall film to improve the combustion efficiency and reduce emissions. A good in-cylinder mixture preparation is not only depends on the in-cylinder flow, but also the spray formation. Since gasoline direct-injection (GDI) multi-hole injectors can reduce smoke emission due to enhanced evaporation and a short liquid core in the spray [1], GDI multi-hole injector has been widely used in the gasoline SIDI engine.

The requirements of the GDI multi-hole injector for a GDI engine are more complicated than the other traditional gasoline injectors, such as swirl injector. In addition to the fuel metering accuracy, cone angle and spray atomization, GDI multi-hole injector need specify number of nozzles, spray pattern which decides the spray plume trajectory, individual plume angle and even the hole-to-hole variation of the mass flow rate. Both automakers and injector manufacturers are putting more and more efforts to optimize the GDI multi-hole injector design for the combustion system to meet fuel consumption and emission requirements.

During the SIDI homogeneous-charged engine development, the spray pattern plays a critical role to achieve homogeneity of mixing and less wall wetting. The spray pattern need be specified by the combustion system designer or the injector supplier, the typical definition process [2] will include three steps: (a) define spray pattern based on the geometric constrains and considering plum deflection due to intake charge motion interactions, (b) CFD in-cylinder mixture preparation analysis at different engine operating conditions, (c) build injector hardware and test. This process is more like a trial-and-error process, it is very time consuming and could take many iterations to finalize the spray pattern.

This paper introduces an automated spray pattern optimization process facilitated by Isight software. Isight is not only used as an optimization tool, it also provides a convenient way to automate the process. The result of the spray pattern optimization example shows significant improve of the air-fuel mixing uniformity.

2. Methodology

3D CFD in-cylinder mixture preparation analysis becomes a major virtual tool for the spray pattern optimization during the combustion system design. To pick up a right spray pattern will involve many iterations of CFD analysis at different engine operating conditions and is very time consuming and computationally expensive. In this section, the traditional way of spray pattern optimization process will be first introduced followed by the innovative automated spray pattern optimization process, which could achieve optimized spray pattern and dramatically reduce the work load of analyst.

2.1 Traditional Spray Pattern Optimization Process

The traditional spray pattern optimization process is shown in Figure 1, it is a trial-and-error process and the spray pattern design is guided by 3D CFD in-cylinder mixture preparation analysis. The spray pattern for a specific combustion system is usually proposed by the designer or the analyst based on the geometry constrains and existing spray pattern for the similar combustion systems. Figure 2 shows how a spay pattern is defined, the foot print of the spray, which is obtained by projecting the spray on a plane perpendicular to the injector axis, is usually used to specify the spray pattern. Designer adjusts the spray foot print to manipulate the spray plume trajectory during the spray optimization process.

The analyst will use the proposed spray pattern to run 3D CFD in-cylinder mixture preparation analysis. The computational domain for CFD analysis will include the combustion chamber, intake runner, intake port and exhaust port, it is a transient analysis using moving mesh technique with typically more than half million meshes. More than one critical engine operating conditions will be used for spray pattern evaluation to ensure achieving good mixing at a wide range of engine operating conditions. Therefore, the CFD in-cylinder mixture preparation analysis is computationally expensive and makes the whole optimization process very time consuming.

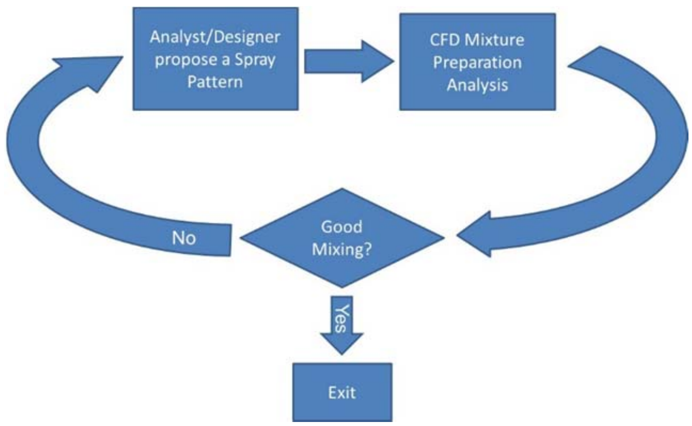
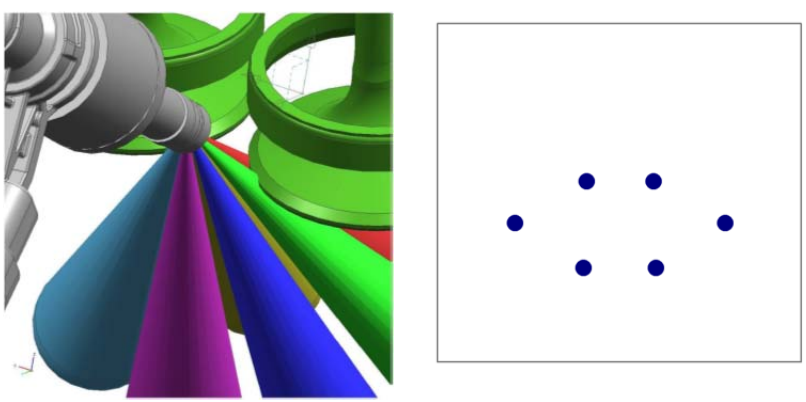


Figure 1. Traditional process of spray pattern optimization

Based on the CFD results, the proposed spray pattern will be used to order an injector hardware for test if the mixing targets are met, otherwise, the designer will propose a new spray pattern based on CFD results and his experience, and the evaluation process will be repeated. The total iteration number of this traditional spray pattern optimization process will largely depend on the designer experience and the combustion system design.



(a) **(b)**

Figure 2. Define a spray pattern (a) Geometry constrains (b) Foot print of spray

2.2 Automatic Spray Pattern Optimization Process

As described in the traditional spray pattern optimization process, designer and analyst have to baby sitter the whole process and manually matching the spray patterns for a specific combustion system at a broad range of operating conditions. The whole process is very time-consuming and there is no optimization algorithm used. In order to reduce the work load of analyst and have a better optimized spray pattern, an automatic spray pattern optimization process has been proposed as shown in Figure 3. Given initial spray pattern following by the CFD in-cylinder mixture preparation analysis, the CFD results will be used as an input for an optimizer, optimizer will generate a spray pattern automatically instead of generating by the designers based on their experience. The air-fuel mixing uniformity is set as the objective of optimizer, during the optimization process, the optimizer will adjust the spray pattern using its optimization algorithm according to the history of CFD results to achieve good mixing.

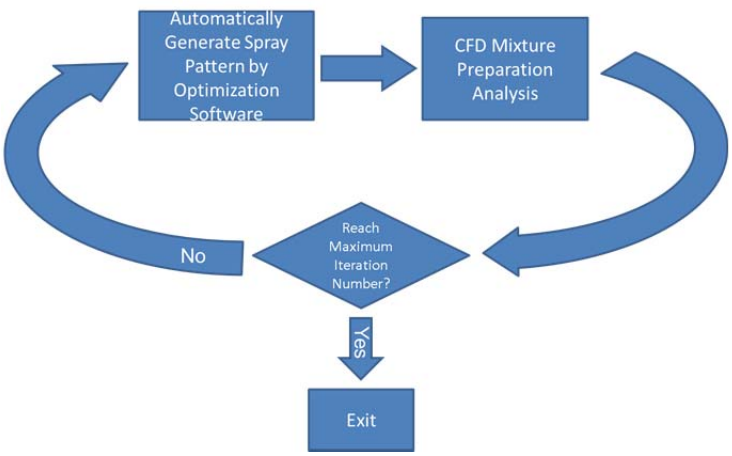


Figure 3. Automatic process of spray pattern optimization

Isight is a product of Dassault Systèmes and is an industry-leading software for process automation and design optimization. It provides a set of process and application components to help automate simulation process and enable users to explore the design space using advanced built-in optimization method. Isight is indeed well suited for this automatic spray pattern optimization process with its ability to drive simulation for optimization. Figure 4 shows the simulation process flow of the spray pattern optimization in Isight. The optimizer, named as “Spray Generator”, is the brain of the process, it controls the design parameters, the optimization method, the objectives of optimization, number of iterations, et al. The simcode component with the name “CFD In-cylinder Analysis” is used to control the 3D CFD In-cylinder mixture preparation analysis, a CFD solver will be called by the simcode component, and the spray pattern generated by "Spray Generator" will be passed to "CFD In-cylinder Analysis" as one of the input. The key results from CFD analysis will be extracted by "CFD Post-Processing", a data exchanger component, and passed to "Spray Generator".

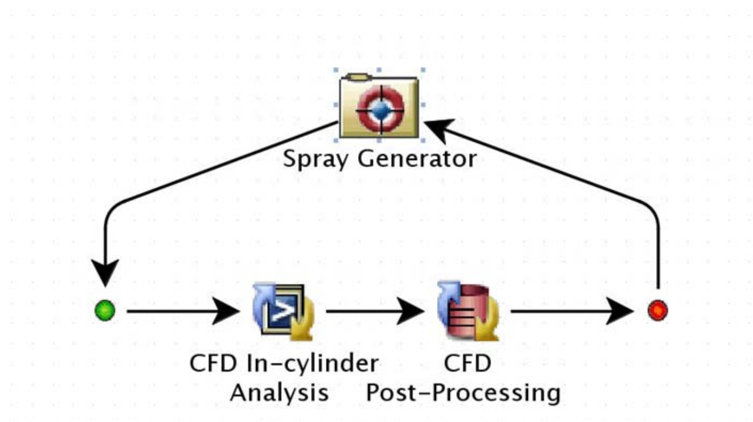


Figure 4. Automatic process of spray pattern optimization enabled by Isight

3. Application of Spray Pattern Optimization

A spray pattern optimization is conducted for a 4-valve side injection SIDI engine using the automatic spray pattern optimization process enabled by Isight. The baseline spray pattern is shown in Figure 5, which has six nozzles and typically symmetrical for a 4-valve side injection engine. The design variables will be the x-y coordinates of the foot print from each nozzle, due to the symmetrical pattern, only the coordinates of four nozzles inside the red circle in Figure 5 will be used as design variables and the number of design variables is reduced from 12 to 6. The baseline spray pattern is initialized in the optimizer component, which is called "Spray Generator" as shown in Figure 4. Based on the CFD in-cylinder mixture preparation analysis results from each iteration, the optimizer will adjust the design variables to give a new spray pattern for next iteration.

The 3D CFD analysis is conducted using the commercial software, StarCD. The Euler-Lagrangian method is used to model the two phase flow in the engine, the spray liquid phase is modeled with Lagrangian particles and coupled with the gas phase. The combustion chamber, intake runner, intake port and exhaust port are discretized with a trimmed mesh which is prepared by es-ice. The size of mesh is typically 1-2 mm and moving dynamically based on the valve lift profile and piston motion. The analysis is started before intake valves opened, portion of the exhaust stroke, the intake stroke and compression stroke are simulated. The valve lift profile, initial and boundary condition are provide by GT-Power and pressure boundary condition are used at inlet and outlet. An in-house spray model [3] is used to model the spray, the spray calculation starts after the primary atomization by injecting droplets representative of post primary atomization. The mixture preparation analysis provides detail information of the charge motion, interaction between spray and air flow, and the statistics of equivalence ratio distribution.

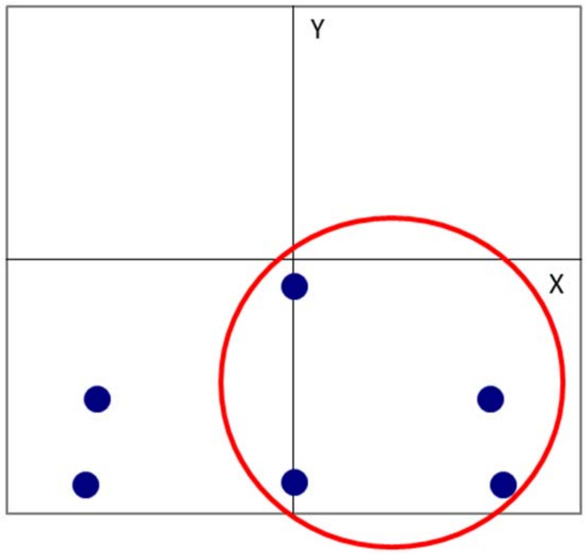


Figure 5. Baseline spray pattern

Three typical engine operating conditions have been used to evaluate the spray pattern, the objectives of the optimization is to achieve homogeneous mixing and minimize the wall wetting to reduce the emission. The standard deviation of equivalence ratio (EQR), which indicates the mixing uniformity, has been calculated in the "CFD Post-Processing" component in Figure 4. The accumulated wall film mass is also collected in the "CFD Post-Processing" component. According to the CFD results, the optimizer in "Spray Generator" will optimize the spray pattern to minimize the standard deviation of equivalence ratio and the wall film mass.

Isight provided different optimization method for users to choose. For the spray pattern optimization, since the effects of spray pattern on the mixing homogeneity is non-linear and complicated, the best choice of the optimizer for a non-optimization expert will be an optimizer which automatically controls a complementary set of optimization method as needed. In this application, the automatic optimization engine, Pointer, has been chosen to optimize the problem. As described in Isight, "Pointer controls four optimization methods: a genetic algorithm, Nelder and Mead downhill simplex, sequential quadratic programming (NLPQL), and a linear solver. This complementary set of algorithms was selected because each succeeds and fails for different topography features. It has been found that a hybrid combination of these methods solves a broad range of design optimization problems. The Pointer Automatic Optimizer can control one algorithm at a time or all four at once. As the optimization is proceeding, the technique determines which algorithms are most successful as well as optimal internal control parameters (step sizes, numbers of iterations, number of restarts, etc).” Pointer is found very efficient and easy to use in this application.

4. Results

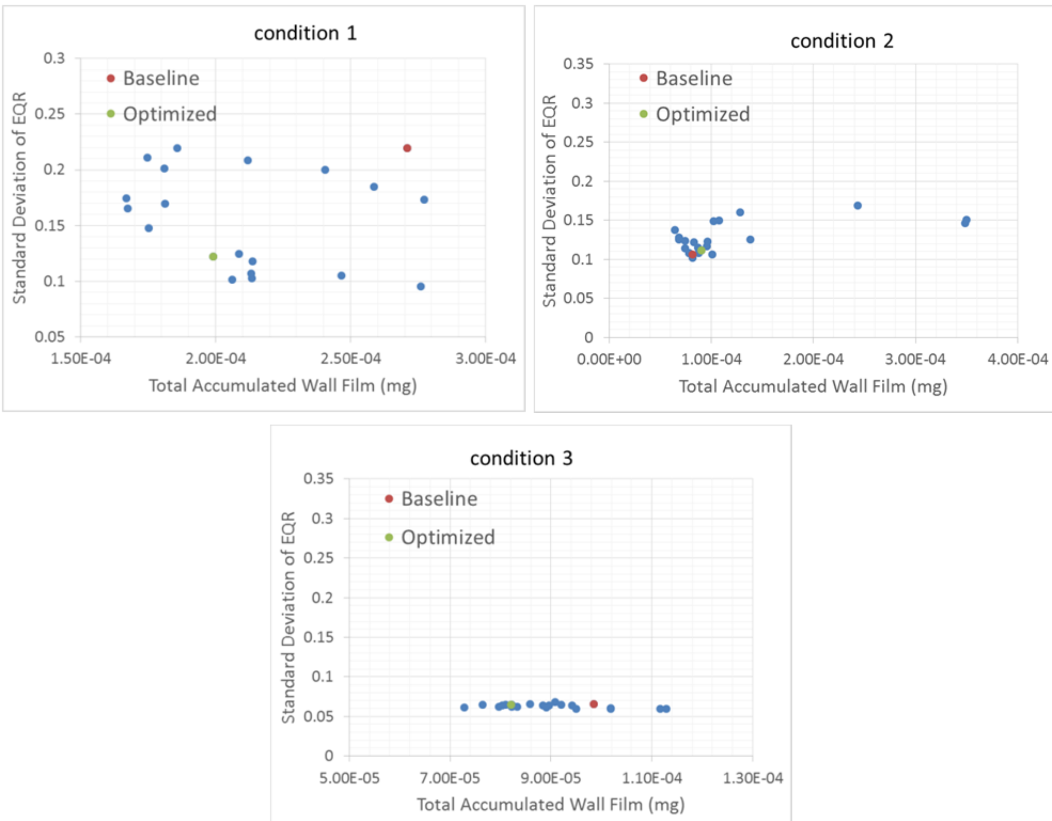


Figure 6. Optimization results of Standard Deviation of EQR v.s. Wall Film

The optimization has been ran for 22 iterations, Figure 6 shows the results of the standard deviation of EQR versus the accumulated wall film mass. As described in section 3, the objective of the optimization is to minimize the standard deviation of EQR and reduce the wall wetting. The baseline result has been indicated as the red circle in Figure 6, it clearly shows large standard deviation of EQR at condition 1 implying stratified mixing at this condition, and good mixing at both condition 2 and 3. The green circle in Figure 6 represents the results using optimized spray pattern. The optimized spray pattern has not only dramatically improved the mixing at condition 1, but also reduced the wall wetting at the same time. By considering multiple operating conditions in this optimization, the mixing at condition 2 and condition 3 is not degraded, and less wall wetting is observed at condition 3.

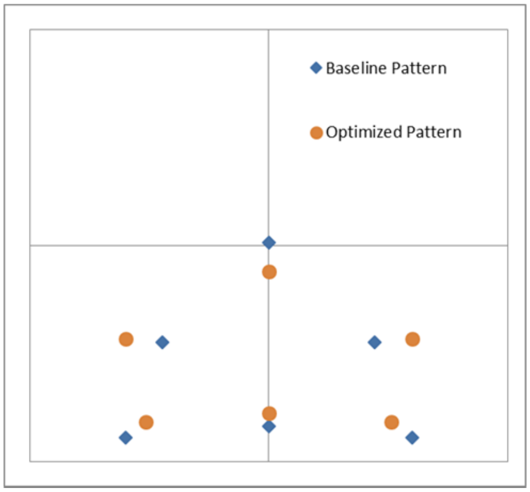


Figure 7. Optimized spray pattern

The optimized spray pattern is shown in Figure 7. Comparing to the optimized spray pattern, the central up plume of the baseline pattern has been tilted down, and central low beam is a little bit up. The side beams of the baseline spray pattern have also been adjusted by widening the up two side beams and bringing the low two side beams slightly up and closer. Figure 8 shows the mixture preparation results using the baseline and optimized spray pattern, the EQR contour at different sections are compared side by side at the three different conditions. The red color indicates the area with rich fuel vapor and blue color is the area with lean fuel vapor. At the condition 1, EQR contour of baseline spray pattern result shows stratified mixing with large regions of lean and rich pockets. The mixing becomes much more uniform by using the optimization spray pattern at condition 1. For condition 2 and 3, the EQR contour shows very similar mixing between the results obtained by baseline and optimized spray pattern.

The optimization process is computationally expensive mainly due to the CFD mixture preparation analysis. The CFD analysis, which will run simultaneously for three operating conditions, takes about 10 to 11 hours to finish for one single run. In this work, it took about 10 days to finish 22 iterations. However, this automatic process is more efficient comparing to the manual process, which has no optimization method involved and uses trial-and-error process based on the designers' experience. This automatic method also reduces the workload of the engineer by saving the model setup time, post processing time and results analysis time.

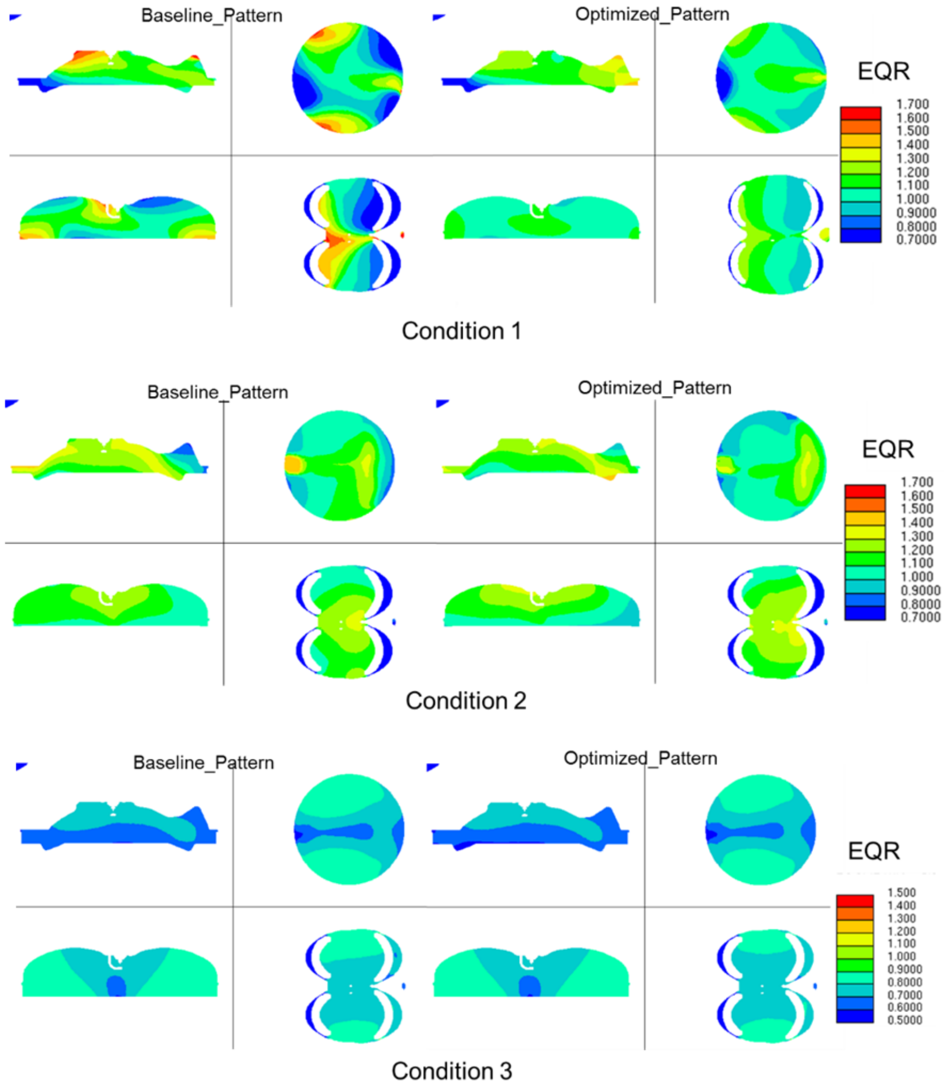


Figure 8. Mixture preparation comparison using baseline and optimized spray pattern

5. Conclusion

The spray pattern optimization for the engine combustion system based on 3D CFD in-cylinder mixture preparation analysis has been automated using Isight. Isight not only gives convenient way to automate the process, but also provides powerful optimization methods, which largely improve the efficiency of this automatic process. This automatic method has been successfully applied in a GDI injector spray pattern optimization based on multiple engine operating conditions for a 4-valve side injection combustion system. The results shows big improvement of the mixing homogeneity with less wall wetting when using optimized spray pattern at one condition, where the baseline spray patters shows worst mixing. Similar mixing is achieved using optimized spray pattern at the other two operating conditions with no significant change of wall wetting. Using this automatic tool could expedite the combustion system development process and reduce the work load of the engine analyst.

6. References

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