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EXPLORATION OF OIL FLOW AND HEAT TRANSFER PHENOMENON FOR GALLERY-COOLED DIESEL ENGINE PISTONS

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ABSTRACT

This paper details the exploration of oil jet piston cooling phenomenon with a focus on heat transfer from the diesel engine piston to the oil. Several numerical methods based on computational fluid dynamics (CFD) and conjugate heat transfer (CHT) were developed to resolve key aspects of piston oil cooling. These methods aim to establish and characterize the flow and heat transfer regimes that are inherent to the piston gallery cooling system, and to assist in quantifying the piston heat transfer and establish its dependence on a number of parameters related to the engine layout and performance, the oil cooling system, and the cooling gallery contained within the piston. Telemetry experimental data from a single-cylinder diesel engine was used to better understand the piston cooling system and to develop and validate modeling and simulation approaches. The combined findings offer a foundation for further study of oil jet piston cooling.

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INTRODUCTION

In June 2021, the National Academy of Sciences released a study report sponsored by the Army DASA R&T, which concluded that "jet propellant 8 (JP8), diesel, and biodiesel should serve as the primary sources of power and energy brought to the battlefield for the foreseeable future" [1]. The report emphasizes that the Army needs to continue improving diesel engines for fuel efficiency, durability, and power output. All three of these factors are dependent on the thermal management of the hottest constituents of the engine, the combustion chamber, valves, and moving piston, which are exposed to extreme heat flux fluctuations during the combustion cycle. Consequently, a significant focus of Army R&D efforts will pertain to the thermal management of diesel engine pistons.

Most of the heat dissipated from the piston pertains to the impingement of an oil jet on the bottom of the piston, with a small portion of heat (5% to 20%) escaping through the piston rings and their interaction with the liner of the engine block [1][7].

Consequently, improving engine thermal management requires a greater understanding of the mechanisms of heat transfer between the oil and the piston. However, gaining such an understanding poses a challenge because of the multifaceted nature of the problem, which includes moving parts (piston, crank shaft, and connecting rod), oil jet break-up due to aerodynamic forces, mixture of two fluids (air and oil), and mixture movement inside the piston gallery. Experimental techniques for substantive quantitative analysis are not practical because of the complex nature of the flow/mist inside the engine crank case and high-speed rotating parts (short time scales) involved.

Perhaps the most practical solution for better understanding piston oil jet cooling is the development and validation of a physics-based computational fluid dynamics (CFD) and conjugate heat transfer (CHT) modeling & simulation (M&S) methodology. Such methodology would resolve the piston cooling jet and enable the understanding of heat transfer pathways by providing insight into the oil flow inside the gallery and the spatial distribution of heat transfer coefficients and oil temperatures that are fundamental for assessing the piston heat transfer.

Parameters of interest

Gallery-cooled pistons are characterized by the presence of an annular cavity that is located between the top and underside of the piston as is shown in Figure 1. For oil to enter and exit this cavity, or gallery, there are two openings on the underside of the piston that are located on opposite ends of the gallery. A nozzle that is mounted in the engine crank case and is pointed at the underside of the piston, towards one of the openings, emits a continuous jet of oil which enters the gallery, impinges on the top of the gallery, and then circulates within the gallery. Since the piston is translating up and down at a fast rate, the oil flows within the gallery in what has been referred to as a “cocktail shaker” motion [8]. After residing in the gallery for a certain amount of time, the oil flows out of it through one of the openings to the underside of the piston. The sum of this process contributes to the transfer of heat that is absorbed by the piston during combustion to the oil.

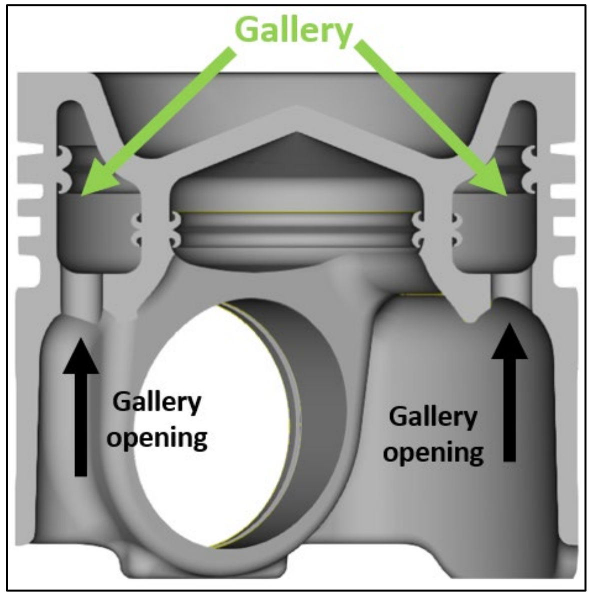

Figure 1: Cross section of a gallery-cooled piston.

A number of parameters related to the engine and cooling system influence the oil flow within the gallery and heat transfer from the piston to the oil. In relation to the engine, the most readily identifiable parameters of interest are the engine speed, the position of the piston during the cycle, the piston stroke length, the connecting rod length, the piston bowl geometry, and the engine load. For the cooling system, the oil flow rate, piston cooling nozzle (PCN) geometry and alignment, oil viscosity, and gallery geometry all play a role in piston cooling.

In addition to these physical parameters, there are also several non-dimensional parameters specific to gallery-cooled pistons that have been proposed by previous authors and appear to merit further investigation. The oil fill ratio (OFR) is defined as a ratio of volume of oil within the gallery to the overall volume of the gallery [2].

$$OFR = \frac{V_{oil}}{V_{gallery}} \tag{1}$$

The gallery catch ratio (GCR) is defined as a ratio of oil volume flow that exits from the gallery at the outlet opening and the oil volume flow that exits from the PCN [3]. The GCR can be considered as a measure of the effectiveness of the oil to pass through the gallery.

$$GCR = \frac{\dot{V}_{out}}{\dot{V}_{PCN}} \tag{2}$$

The inlet catch ratio (ICR) is defined as a ratio of the oil volume flow rate that enters the gallery through the gallery inlet opening and the volume flow rate of oil that exits from the PCN [3]. The ICR can be useful when considering the short circuiting of flow within the gallery and the misalignment of the PCN with the gallery inlet opening.

$$ICR = \frac{\dot{V}_{in}}{\dot{V}_{PCN}} \tag{3}$$

METHODOLOGY

Three different modeling methods were employed to explore the piston cooling phenomenon. A computationally inexpensive “Body Force” method was developed to allow for a parametric study of many of the gallery flow characteristics. An adaptive mesh refinement “AMR” method was developed to study the effect of the alignment of the PCN on gallery filling and heat transfer boundary conditions. Lastly, a method referred to as the “Overset” method comprises the most comprehensive working model of the cooling system in that it aims to resolve the piston gallery cooling flow and heat transfer from the structure to the piston simultaneously. All three of these methods employ multiphase computational fluid dynamics finite volume software for their application. The time-averaged Reynolds-averaged Navier Stokes (RANS) equations were used to model fluid flow with the realizable k-ε turbulence model. The volume of fluid (VOF) method was used for modeling the interface between the two phases (air and oil) [4].

1.1. Body Force Method

The Body Force method considers only the domain of the piston gallery itself as is shown in Figure 2. Gravity and the body force induced by the reciprocating piston motion are accounted for by adding a source term to the momentum equation. The oil jet that impinges on the gallery is simplified with a velocity inlet boundary condition at the gallery inlet as is shown in Figure 3. Additionally, the flow on the piston underside and below the piston is not considered. What makes this method valuable is a relatively quicky simulation time, which makes it tractable for parametric studies relating to the flow and resulting convective boundary conditions in the gallery.

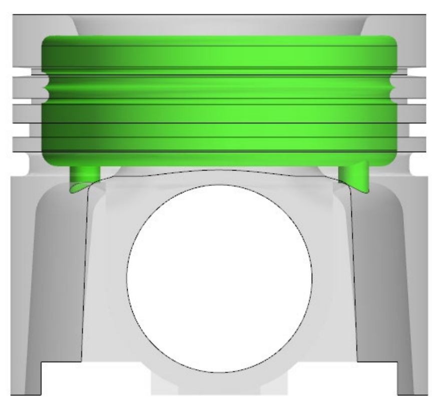

Figure 2: Body Force method flow domain.

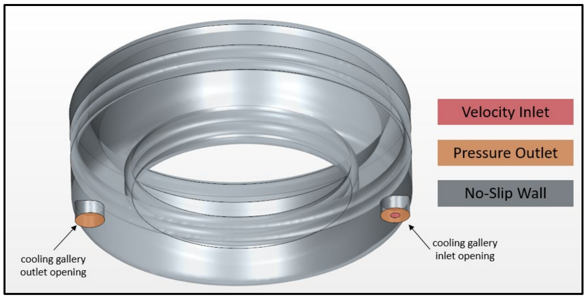

Figure 3: Body Force model boundary conditions.

1.2. AMR Method

The AMR method employs the CONVERGE CFD solver to study the effects of PCN alignment on gallery filling and convective heat transfer boundary conditions as is shown in Figure 4 [5]. This method considers the domain of the piston gallery and underside, the cylinder liner, and the PCN. The model constructed for this method employs an adaptive mesh to account for piston motion and to capture the interface between oil and air. This method of mesh refinement lends itself well for studying PCN misalignment because it ensures adequate mesh resolution at the oil/air interface without relying on a priori knowledge of the locations in the flow domain that oil can potentially occupy.

Figure 4: Oil flow predicted by AMR model for a misaligned PCN at piston bottom dead center.

1.3. Overset Method

The Overset method is the most comprehensive of the methods in that the piston gallery cooling flow and the piston structure heat transfer are resolved simultaneously as is pictured in Figure 5. To account for the motion of the piston relative to the cylinder and piston cooling nozzle, the overset, or chimera, mesh method is employed [6]. Heat exchange is modeled between the multiphase oil-air fluid domain and the solid domain of the metal piston. The model that uses this method calculates the convective boundary conditions (heat transfer coefficient and reference temperature) for the piston gallery in the fluid domain and applies them to the gallery walls of the solid domain. For the piston undercrown, skirt, lands, and ring grooves, fixed values for the convective boundary condition are assigned. A heat flux boundary condition is applied to the top of the piston. These aforementioned boundary conditions are used to predict the piston temperature for the solid domain using a coupled finite element model. The predicted temperatures on the piston surfaces that are adjacent to the fluid domain are mapped onto the boundaries of the fluid domain. Currently, the PCN is simplified in the model as a straight tube.

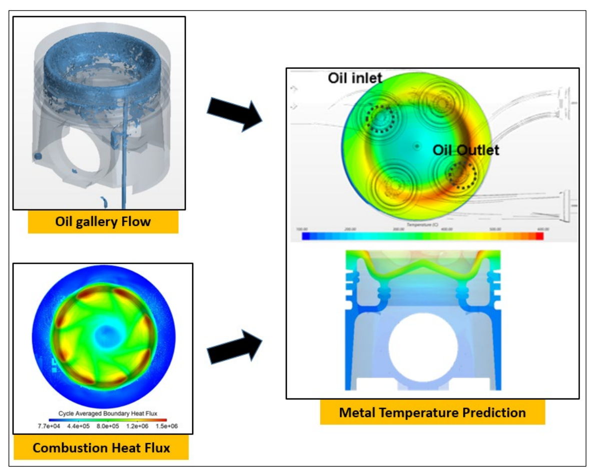

Figure 5: Overset method approach.

EXPERIMENTAL DATA

Telemetry piston data collected from experiments conducted in the Ground Vehicle Power and Mobility (GVPM) Laboratory single-cylinder diesel engine cell was used to better understand the piston cooling system and to validate modeling methodologies. The data pertained to measurements from thermocouples located 1 mm below the top surface of the piston as is shown in Figure 6.

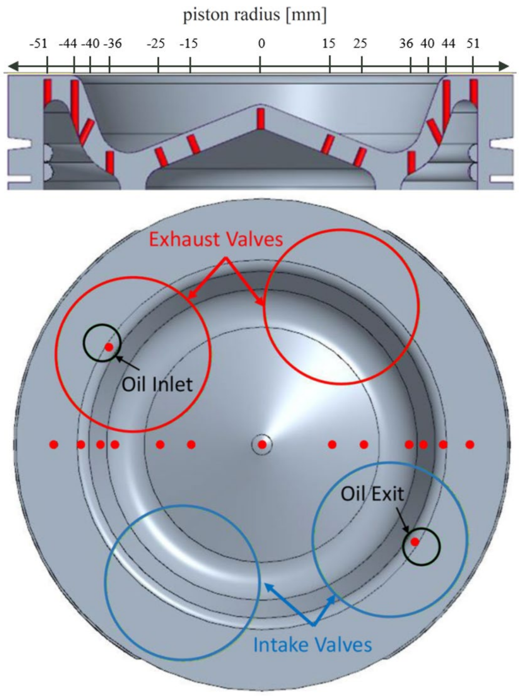

Figure 6: Thermocouple locations.

Additionally, a test was developed and conducted in the GVPM single-cylinder diesel engine cell to quantify the PCN alignment impact on the cooling gallery inlet flow. The test was conducted manually by rotating the crank to different positions, as any type of flow measurements inside the rotating engine are nearly impossible. The alignment of the PCN impacts the amount of oil that can enter the cooling gallery and subsequently affects the flow inside the gallery and piston heat transfer. The goal of this novel test was to characterize the alignment of the PCN and gallery inlet by capturing and measuring the oil leaving the gallery outlet. To capture the oil leaving the gallery, a piston was instrumented to allow for a fitting and tubing to be attached as is shown in Figure 7. The oil leaving the cooling gallery was routed through the tubing outside of the crank case and measured by weighing it.

Figure 7: PCN alignment test instrumented piston.

RESULTS

The Body Force method provides valuable insight into the distribution of oil within the piston gallery during engine operation as is shown in Figure 8. It is possible to observe that during the downward stroke, the piston accelerates downward from top dead center (TDC) and the oil is driven to the top of the gallery. As the piston further approaches bottom dead center (BDC), the oil starts to flow towards the bottom of the gallery which is primarily due to the deceleration of the gallery as it approaches a temporary standstill at BDC. The oil is then driven further to the bottom of the piston as it accelerates upward during the up stroke. As the piston decelerates as it approaches TDC during the second part of the upstroke, the bulk of the oil again moves towards the top of the gallery. The greatest outflow of oil from the gallery occurs when the piston is in a range of positions near BDC. This is due to the deceleration of the piston before BDC and its acceleration after BDC.

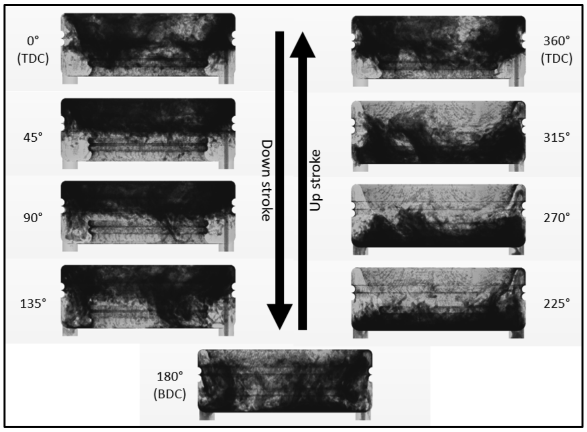

Figure 8: Distribution of oil within the moving piston gallery for different crank angles predicted with the Body Force model.

Figure 9 shows the Body Force model predicted average heat transfer coefficients (HTC) for different sections of the gallery for two PCN oil flow rates of 4.7 and 8.9 L/min and two engine speeds of 1700 and 2500 rpm. These limited results suggest that the PCN oil flow rate may have a more significant impact on piston heat transfer than engine speed.

The AMR method demonstrates that the alignment of the PCN affects oil jet breakup and the amount of oil that enters into the gallery. In Figure 10, the transient average HTC for the cooling gallery is compared for two cases: one where the PCN is aligned so that it is directly perpendicular to the gallery inlet opening, and another where the PCN is tilted by 2-degrees from perpendicular towards the center of the piston. The plot in the figure shows that when the nozzle is aligned with the gallery inlet opening, the HTC is notably greater than that obtained with PCN aligned 2-degrees off-perpendicular. This type of result for the cooling gallery would be expected a priori, but what would perhaps not be expected is the effect that PCN alignment has on the heat transfer along other parts of the piston. In Figure 11, the transient average HTC for the piston undercrown is compared for the aligned PCN and the 2-degree off-perpendicular PCN. The HTC for the undercrown is seen to be greater when the PCN is off-perpendicular to the gallery inlet opening than when it is aligned. In the off-perpendicular case, while not all of the oil released by the PCN enters the cooling gallery, some it if does impinge on the bottom of the piston, which contributes to better heat transfer on the undercrown. These results indicate that there is value in considering the impact that the oil jet may have on the piston underside with PCN misalignment and not limit interest solely to the cooling gallery when considering gallery-cooled piston heat transfer.

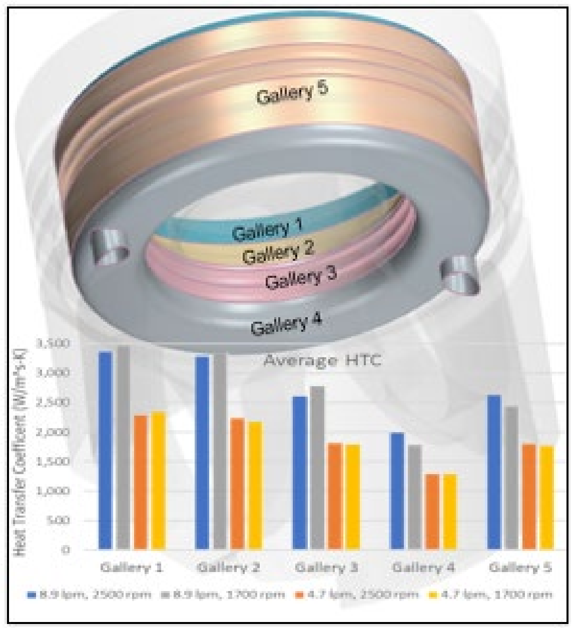

Figure 9: Predicted average gallery section HTC for different PCN flow rates and engine speeds.

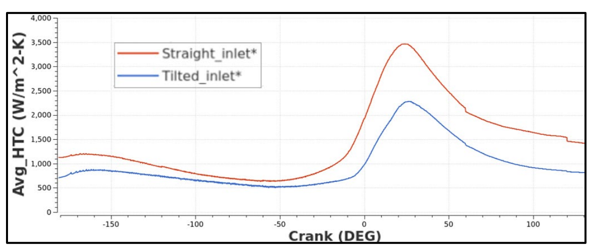

Figure 10: Average cooling gallery HTC with PCN orientation.

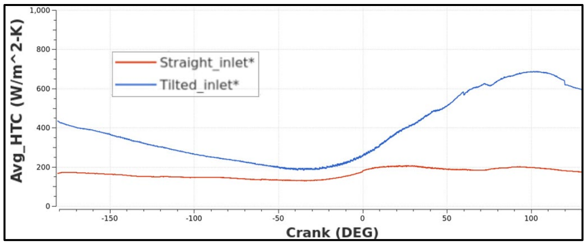

Figure 11: Average undercrown HTC with PCN orientation.

Figure 12 depicts the cycle-averaged convective boundary conditions that were predicted for the gallery using the Overset method model. High HTC values were predicted directly above the gallery inlet opening on the top surface of the gallery upon which the oil jet issued by the PCN impinges. The model additionally predicted a higher reference temperature by the gallery outlet opening, which correlates to a higher oil temperature leaving the gallery than entering it through the inlet opening. This result is expected as the oil picks up heat from the piston during its residence in the gallery.

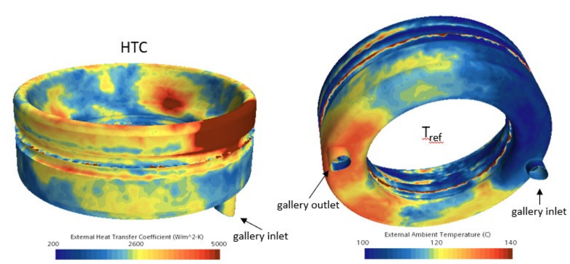

Figure 12: Overset model presided convective boundary conditions.

Figure 13 depicts the predicted temperature profile for the piston with the Overset method model. The highest temperatures are predicted to occur along the piston bowl rim. Additionally, the model predicts that the section of the bowl rim above the gallery outlet opening will exhibit greater temperatures than the section of bowl rim above the gallery inlet opening. This prediction correlates with the convective boundary conditions shown in Figure 12 and with experimental measurements showing this same trend in temperature difference by the piston surface depending on the location of the bowl rim relative to the gallery inlet and outlet openings. Figure 13 additionally compares the thermocouple telemetry engine piston data from single-cylinder research engine testing to CFD predictions of the Overset model. The Overset model was found to underpredict temperatures for the piston bowl rim and the top edge of the piston while overpredicting the temperatures on the piston crown. However, the model did predict the trend in the experimental data pertaining to the temperature measurements for the piston bowl rim above the gallery openings where higher temperatures were measured above the gallery outlet opening than above the gallery inlet opening.

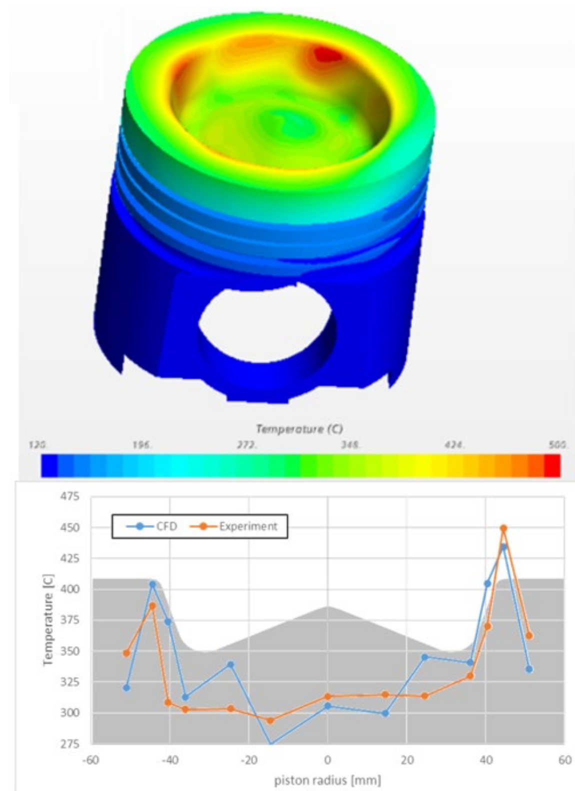

Figure 13: Predicted piston temperatures with Overset model.

The PCN alignment test considered the two PCNs used in the single-piston engine. The experimental setup method was found to have a few limitations—namely, there was constraint in the oil flow leaving the piston as a result of the diameter of the tubing that was used—but valuable information was still gained. Figure 14 shows the outlet mass flow rate as a percentage of the PCN mass flow rate for the two PCNs. Comparing the performance of the two PCNs shows that the alignment of PCN 1 and 2 does in fact vary, and that, overall, PCN 2 shows better alignment with the inlet to the cooling gallery than PCN 1. Since these nozzles are used for experiments, their alignment should be considered in future studies when assessing model predictions with test data.

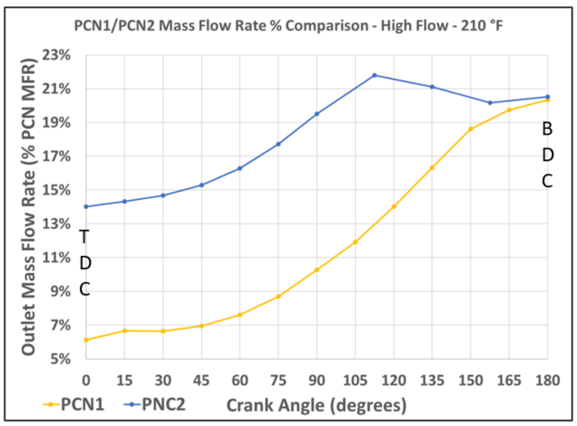

Figure 14: PCN alignment test data.

SUMMARY & CONCLUSIONS

The methods and results described above have contributed to a broader understanding of the oil flow and transfer phenomenon for gallery-cooled diesel engine pistons. They will additionally act as a foundation for further study of oil jet cooling. In this respect, future efforts should closely examine the geometry of the PCN and its effects on oil flow. Based on the importance of PCN alignment that was observed, the breakup of the oil jet that issues from the PCN can also be expected to play a significant role in piston-to-oil heat transfer as oil jet breakup also affects the amount of oil that enters the piston gallery.

Windage effects on the oil flow should also be considered for future studies. This is difficult to assess using traditional mesh based CFD methods because of the many moving parts involved such as the piston, the connecting rod, and the crank shaft. A meshless method should most likely be considered for such a study, such as smoothed-particle hydrodynamics (SPH).

Lastly, future efforts should consider the convective boundary conditions for the piston skirt, lands, and undercrown, which this study did not. With these considerations in mind, the ability to construct a comprehensive model of the piston cooling system appears to be a feasible outcome. Such an accomplishment would enable the study of the impact of a wide range of engine parameters, piston cooling configurations, and operating conditions on piston heat transfer.

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