

Piston Cooling Nozzle Oil Jet Evaluation Using CFD and a High Speed Camera

Jordan Kelleher and Nikhil Ajotikar
Cummins Inc.

ABSTRACT

Piston cooling nozzles/jets play several crucial roles in the power cylinder of an internal combustion engine. Primarily, they help with the thermal management of the piston and provide lubrication to the cylinder liner and the piston's wrist pin. In order to evaluate the oil jet characteristics from various piston cooling nozzle (PCN) designs, a quantitative and objective process was developed. The PCN characterization began with a computational fluid dynamics (CFD) turbulent model to analyze the mean oil velocity and flow distribution at the nozzle exit/tip. Subsequently, the PCN was tested on a rig for a given oil temperature and pressure. A high-speed camera captured images at 2500 frames per second to observe the evolution of the oil stream as a function of distance from the nozzle exit. An algorithm comprised of standard digital image processing techniques was created to calculate the oil jet width and density. Finally, the results of the CFD model were compared to the key metrics identified by the high-speed imaging and were found to be in good agreement. It was discovered that the percentage deviation between the CFD model's velocity profile along a line at the PCN exit and a perfectly uniform, symmetric profile was a good indicator of the oil jet quality. Therefore, the CFD method has been validated using experimental observations, so it can be implemented to optimize novel PCN concepts early in the development process long before the stages when hardware is procured.

CITATION: Kelleher, J. and Ajotikar, N., "Piston Cooling Nozzle Oil Jet Evaluation Using CFD and a High Speed Camera," *SAE Int. J. Commer. Veh.* 9(2):2016, doi:10.4271/2016-01-8100.

INTRODUCTION

Increasing fuel economy has been one of the main focuses of the automotive industry for the past decade and will likely continue to impact engineering decisions for the next decade. One way to improve fuel economy is to decrease the parasitic losses of the engine. A smaller oil pump, which is driven by the engine, would require less power to operate and thus improve the overall engine efficiency. Oftentimes, over half of the total power draw on the oil pump and lubrication system is due to the piston cooling nozzles (PCN). For example, the flow rate through each PCN on a heavy-duty diesel engine is roughly 3 gpm (11.4 liter/minute), thus, a total of 18 gpm (68.1 liters/minute) for a six cylinder engine. If the PCN design could be optimized such that the oil jet was directed precisely where it is needed then it is feasible that the same cooling effect and heat transfer could be achieved with a lower flow rate. Therefore, a smaller oil pump could be used which would logically lead to an increase in overall engine efficiency and benefit fuel economy.

The region that most needs the PCN oil for heat transfer is the underside of the piston bowl (i.e. cooling gallery). Oil from the PCN enters the piston's cooling gallery and then exits due to gravity and the reciprocating motion of the piston (see [Figure 1](#)). During the brief amount of time that the oil is in the cooling gallery, it is estimated that its temperature increases by 20°-30°C. Following the Arrhenius equation, the oil oxidation rate is generally expected to double for every 10°C increase in temperature [1]. As oil oxidation increases, the oil degrades, becomes more acidic and corrosive, loses its

lubricity, and other harmful consequences. Appropriately, improving the life span of the engine oil is another big challenge for the commercial, heavy-duty diesel market. Premature oil degradation requires more frequent oil changes which is incredibly costly for companies with large fleets of trucks. Since the oil oxidation is known to increase exponentially with temperature, the PCN is a prime suspect in abetting the premature degradation of oil.

Previous work to optimize the PCN design and performance (i.e. oil jet) has been minimal. If the piston temperatures were acceptable and within prescribed limits, then no further consideration was given to the PCN since it had fulfilled its primary function. However, as combustion, and hence piston, temperatures continue to rise to meet emissions regulations or enhance power density, the performance of the PCN will face more rigorous demands. A combination of new piston cooling gallery geometry and PCN concepts were explored experimentally by Thiel et al. [2] to improve the cooling efficiency. A significant reduction in piston temperatures, as much as 25°C at the center of the piston bowl, were achieved for some configurations. However, the design of the PCN was not studied but only where the PCN is mounted (e.g. thrust or anti-thrust side of the piston) and whether one or two PCN's were used per cylinder. Several related studies have simulated heat transfer of the piston and the effects of the PCN using CFD models [3, 4, 5]. While these studies provide great insights into the cooling process and the analytical methods used to predict piston temperatures, the oil jet from the PCN is over-simplified and the oil spray dispersion is not considered. If the oil spray dispersion were included, then the oil film ratio (i.e. volume of oil in the

cooling gallery to the total volume of the cooling gallery) would decrease since not as much oil would enter the cooling gallery inlet hole which will then impact all of the subsequent heat transfer results.

One of the objectives of this study was to formulate a CFD analysis approach/methodology to predict the impact of nozzle design on the oil flow. In principle, Scaled Resolved Simulation (SRS) methods that can model the free jet of any fluid have the ability to perform the intended function stated above. However, these methods include Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) techniques which are computationally expensive and practically cannot be used for industrial applications where multiple nozzle designs need to be analyzed. The simplified CFD approach developed herein does not model the actual oil jet. The analysis procedure models the nozzle component and predicts the flow conditions at the nozzle tip. It is hypothesized that the flow conditions at the nozzle tip can be related to the oil jet quality at several inches away from the tip. If a well-developed and uniform flow field is obtained at the nozzle exit/outlet plane then a better jet quality is expected. This hypothesis was verified through experimentation which will be discussed later.

High-speed imaging accompanied by digital image processing has been used to visualize and characterize the flow from a variety of sources [6]. The plume morphology from fuel injectors was analyzed using a high-speed camera and macroscopic spray parameters, such as spray angle, were identified for several fuel types [7]. Additionally, in-cylinder images of a spray-guided spark-ignited direct-injection engine were analyzed using particle image velocimetry to understand the conditions leading to misfire events and partial burn [8], and in a diesel engine to study the injected fuel jet, combustion process, and soot distribution [9]. Oil jet breakup, localized boiling, and mist generation from a PCN was captured with a high-speed camera by Agarwal and Goyal though no quantitative analysis was performed on the images [10]. In a simplified piston cooling gallery with water, the gas-liquid flow was captured with a high-speed camera while oscillating at various speeds to mimic the piston's reciprocating motion to explore the heat transfer mechanisms [11]. Numerous investigations have been performed to visualize the fluid dynamics of an engine's power cylinder, though none have focused on the PCN and how the quality of its oil jet could affect piston cooling.

As previously mentioned, the current study was motivated by escalating demands to increase engine efficiency and the life span of engine oil. However, a method to objectively and quantitatively characterizing the functional performance of various PCN designs was lacking which was the purpose of this investigation. The PCN design space is extensive even for such a seemingly simple component. Some of the key design parameters to be considered are: the bend radius of the tube, the tube length before and after the bend, the tube inner diameter before and after the swage (i.e. reduction in cross-section), the tube length before and after the swage, how to attach the PCN to the cylinder block (e.g. banjo bolt), etc. The oil jet for several PCN designs was evaluated by initially simulating the flow in a CFD model and later by acquiring high-speed images of the oil stream in an experimental rig setup.

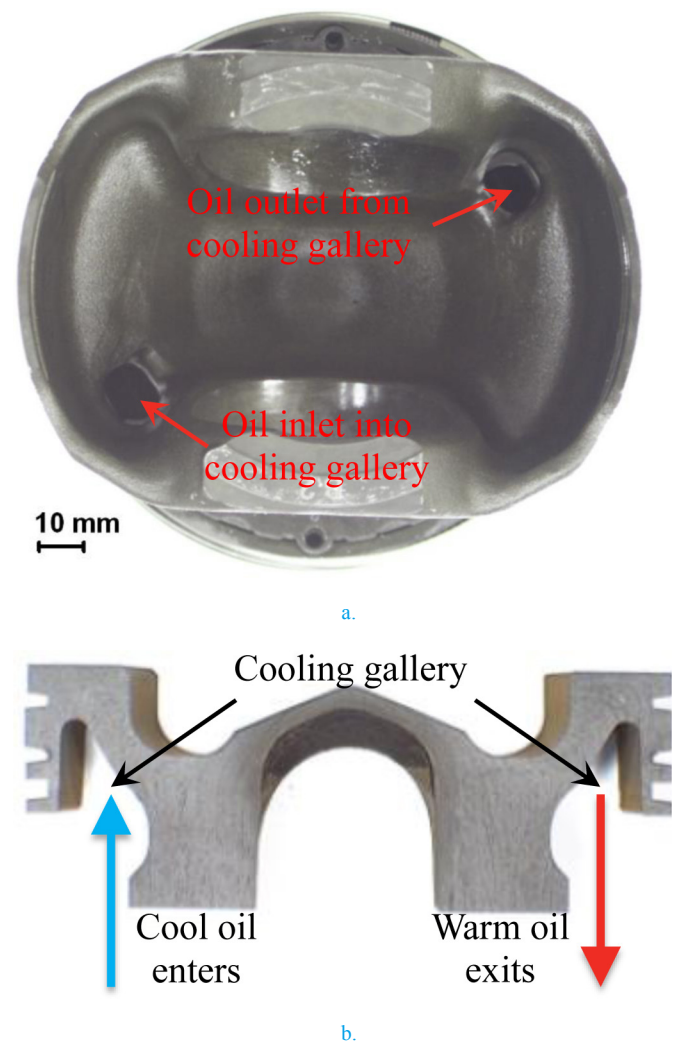


Figure 1. (a) A view of the underside of a piston showing the inlet and outlets of the cooling gallery. (b) A cross-section of a piston (though not the same design as the piston in Figure 1a) revealing the cooling gallery and arrows indicating the oil's path.

MATERIALS

The four PCN designs that were evaluated in this investigation are shown in Figure 2. Each had an inner diameter of 3.5mm and a flow rate of approximately 2.5 gpm (9.5 liter/minute). The tube length after the swage was always 18mm but the tube length before the swage (i.e. after the 90° bend) was varied. The nozzles are labeled based upon their length: (1) Long - an additional 48mm tube length and a 14mm bend radius, (2) Medium - an additional 20mm tube length and a 14mm bend radius, (3) Short - no additional tube length and a 10mm bend radius, and (4) Reference - an additional 48mm tube length but no bend (i.e. straight tube). The reference nozzle obtained its name because the oil jet from a straight tube is the best possible performance that can be achieved.

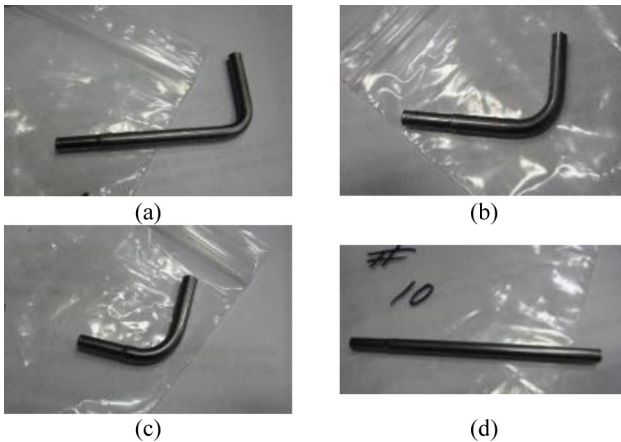


Figure 2. The four PCN designs tested. (a) The long nozzle - an extra 48mm tube length and a 14mm bend radius. (b) The medium nozzle - an extra 20mm tube length and a 14mm bend radius. (c) The short nozzle - no extra tube length and a 10mm bend radius. (d) The reference nozzle - a straight tube with an extra 48mm length.

ANALYTICAL METHODS

Fluid Volume Geometry

Fluid volume representation for two of the nozzles with the upstream fittings is shown in [Figure 3](#). PCN fluid volume takes into consideration the nozzle geometry and any upstream fitting that may have the potential to influence the flow distribution at nozzle tip.

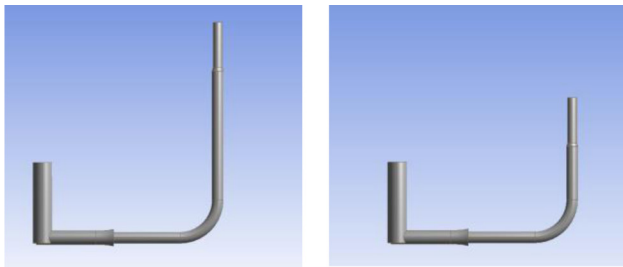


Figure 3. Fluid volumes for (a) The long nozzle - an extra 48mm tube length and a 14mm bend radius. (b) The medium nozzle - an extra 20mm tube length and a 14mm bend radius.

CFD Model Setup

Fluid volume for the PCN was meshed with tetrahedral meshing elements with the use of inflation/boundary layers. Total mesh size for the baseline model was approximately 850,000 elements. Meshing was performed in ANSYS® Meshing.

The inlet boundary for the fluid domain was treated as a “Pressure Inlet.” On the test setup, the nozzle was exposed to the system pressure of 35 psi on the upstream side. The same pressure (35 psi gauge) was applied at the inlet boundary of fluid domain. The outlet boundary of the fluid volume was treated as a “Pressure Outlet” with atmospheric pressure conditions. The realizable k-epsilon model was used to model turbulence, and scalable wall functions were used to consider near wall effects. The properties for the oil density and

viscosity were 825 kg/m³ and 0.00789 Pa-s, respectively, corresponding to 10W-30 oil at 110°C which mimics the rig test conditions.

The CFD analysis was run with Fluent 15.0 steady isothermal incompressible solver. The analysis was executed until the convergence criteria (i.e. two orders of magnitude below the default criteria, 1e-5) was met.

EXPERIMENTAL METHODS

Rig Setup

The rig created to evaluate the oil jet from various PCN designs is shown in [Figure 4](#). The PCN was installed on top of the rig frame and sprayed oil downward in the container and drained back to the reservoir. The rig casing was equipped with transparent, polycarbonate walls to allow visual access to the oil jet. An electric pump was used to draw 10W-30 Valvoline™ Premium Blue™ diesel engine oil from a reservoir and increase the pressure. The oil pressure was continuously monitored in the PCN mounting block via a pressure transducer and maintained at 35 psi (0.24 MPa). The oil in the reservoir was heated by an electric heater and an E-type thermocouple in the PCN mounting block measured the oil temperature which was kept at 230°F (110°C). Any extra plumbing devices (e.g. fittings) that might introduce artificial flow disturbances immediately upstream from the PCN were minimized in order to closely replicate the mounting configuration in the cylinder block.

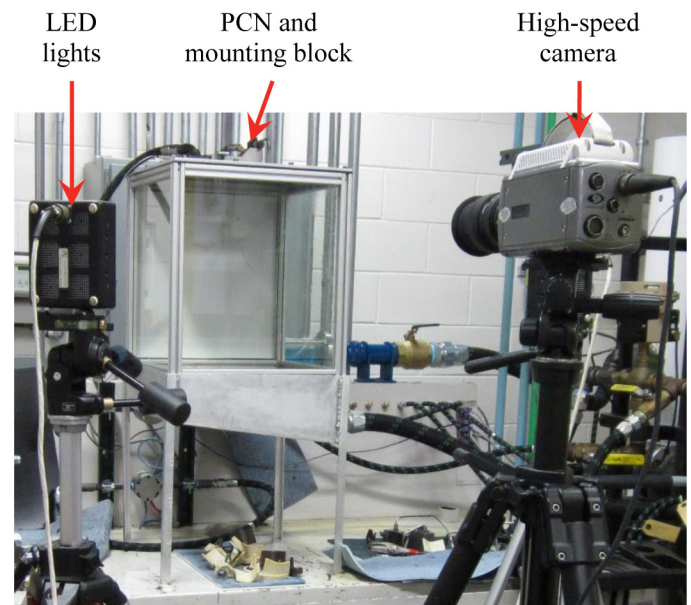


Figure 4. The PCN experimental rig setup.

A digital high-speed camera (Phantom® V5.2, Vision Research, Inc.) equipped with a macro lens (Sigma 24-70mm f/2.8 EX DG) was used to acquire images of 896 x 304 pixels at 2500 frames per second with an exposure time of 60 microseconds. Two 4 x 6 arrays of LED lights (Model 900445, Visual Instrumentation Corporation) with an output of 6000 lumens each illuminated the oil flow. A white background was added to the rig case to assist with the illumination of the oil jet.