

Oil Transport from Scraper Ring Step to Liner at Low Engine Speeds and Effect of Dimensions of Scraper Ring Step

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ABSTRACT

In gasoline engines, a scraper ring with a step on the bottom outer edge is widely used as a second ring. However, there lacks a fundamental understanding on the effects of this feature and its dimensions on oil transport. Inspired by observations from visualization experiments, this work combining computational fluid dynamics (CFD) and theoretical analysis shows that oil can be trapped in the space bordered by a second ring step and the chamfer of a piston third land. The trapped oil can be released to a liner when the piston is approaching the top dead center (TDC). This additional oil on the liner becomes a potential source of oil consumption. Such oil transport has been observed at typically less than 1500rpm. Since road vehicles often operate in this speed range, the newly-observed oil trapping and release can be closely associated with oil consumption in gasoline engines. In this work, a comprehensive study on oil trapping and release will be demonstrated. Computational simulations indicated that oil trapping resulted from the balance between surface tension and inertia. A theoretical model based on the primary physics will be demonstrated. The modeling results satisfactorily matched with experiments and computational simulations. The model indicated that oil trapping in a scraper ring step, as well as oil release to a liner, can be controlled by the geometry of the step. Effects of a few dimensions of a scraper ring step will be described.

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INTRODUCTION

In modern gasoline engines, a scraper ring with a step recessed from the lower outer edge has become a common design for the second ring in a piston-ring pack. The step can be either a rectangular cut or a hook-shaped undercut. The latter design is usually called a "Napier ring". A chamfer on the top of a piston third land effectively enlarges the volume of a scraper ring step. The chamfer will be considered as an integrated part of a scraper ring step in this work, unless specially indicated.

Although previous study suggested that a scraper ring step can provide a reservoir for oil [1], the effect of its geometry and dimensions on oil transport and oil consumption has not been completely understood. Dimensions of a scraper ring step are still design options to improve oil consumption performance of gasoline engines. A good understanding of their effects on oil transport can help rationalize the design decisions and reduce the number of design iterations. It also potentially introduces more considerations to the standards of scraper ring design, for instance, the ISO 6623 standard [2].

In this work, an oil transport mechanism that is closely associated with the dimensions of a scraper ring step will be described. Particularly, at low engine speeds, oil can be trapped in the step of a scraper ring. The trapped oil can possibly be pumped into the second ring groove or released to the liner to increase the local oil film thickness. Both results may increase the oil consumption.

This study was originally motivated by the latter one, that is, oil release to the liner. In literature, oil release from a piston-ring pack to a liner has been termed "bridging" [3, 4]. Previous studies [3, 4, 5, 6, 7] demonstrated that bridging occurs when the inertia of a piston (hereafter called 'body acceleration' to distinguish with the inertia of oil) is sufficiently large to drive oil to the top of a piston land before spreading to the liner. Thus, bridging occurs at high engine speeds, typically above 3000rpm. However, in a recent experimental study by Zanghi [8], bridging was observed at less than 1500rpm, at which the body acceleration is not sufficiently large. Readers are referred to Figure 3-12 in [8] for an evidence of bridging at 1500rpm.

For coherence, an experimental evidence of bridging at 800rpm is shown in Figure 1(c), with generous courtesy of Zanghi. It was taken in a 2D-LIF experiment, which allows an observation of oil distribution through a transparent window in the liner [1, 8], as is shown in Figure 1(a). The design of the test engine is shown in Figure 1(b). There is an undercut in the second ring and a chamfer on the upper edge of the piston third land. Figure 1(c) was taken slightly before the top dead center (TDC). A brighter color indicates more oil, and a darker color indicates less oil. The bright vertical stripes in the vicinity of the piston third land are evidences of bridging. They indicate that oil has been attaching to the liner, which is moving downwards relative to the piston.

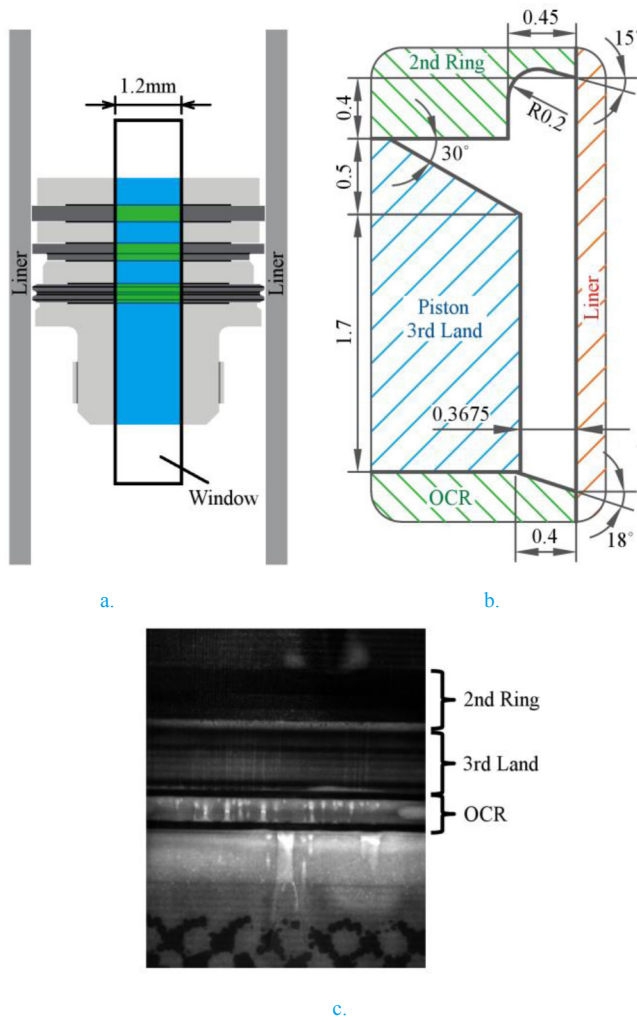


Figure 1. Bridging at 800rpm. (Courtesy of Zanghi.)

In terms of oil consumption, bridging is of significant interest because it can increase oil consumption if occurring before TDC [4]. It introduces additional oil to the liner, and the additional oil supply occurs above an oil control ring. Thus, bridging makes an oil control ring lose control of the oil film thickness on a liner. Since automotive engines mostly operate at low speeds during city driving, low-speed bridging can be closely associated with the overall oil consumption. An in-depth understanding on low-speed bridging potentially contributes to designers' knowledge on oil consumption and lead to better design of a piston ring pack.

In this work, a comprehensive study on low-speed bridging will be presented. Computational simulations will first be demonstrated to reveal the physics behind low-speed bridging. Particularly, oil can be trapped in a scraper ring step and the trapped oil can result in bridging. It is entirely different from the high-speed bridging studied in previous work [3, 4, 5, 6, 7]. Then, a quantitative model on oil trapping and low-speed bridging will be presented. The modeling results implied that oil trapping and low-speed bridging are directly associated with the geometry of a scraper ring step. The effects of a few dimensions of a scraper ring step will be discussed.

COMPUTATIONAL SIMULATIONS

In Figure 1(c), there is a bright horizontal stripe at the bottom of the second ring, indicating considerable amount of oil in the step. Given that body acceleration is not sufficient to drive oil from the third land to supply bridging, the oil in the step is a very probable source of bridging. Though this is not directly evident from the experiment, computational simulations revealed that the oil in the step is indeed the source of low-speed bridging.

In this section, all the simulation results to be shown demonstrate oil transport in a radial cross section like Figure 1(b). They were obtained with an OpenFOAM multiphase solver, interFoam. Piston was taken as the reference frame and liner moves. The unsteady body acceleration, as shown in Figure 2, was incorporated in the solver by Wang [5]. The simulations were two-dimensional, and small clearances were neglected. The results implied that these simplifications would not conceal the essential physics behind oil transport. Each simulation started with an arbitrary oil distribution in a scraper ring step and on a third land. It would be continued until the oil transport reached a revolutionary periodic pattern. Then, the results would be analyzed.

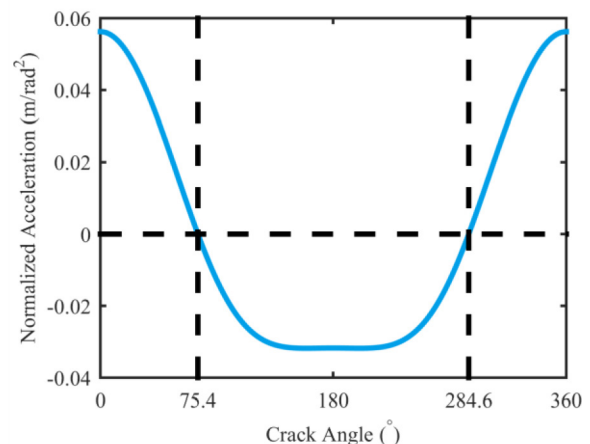


Figure 2. Body acceleration normalized by square of engine speed, upward positive. (Length of connecting rod: 158mm; crank radius: 44mm. 0° crank angle corresponds to TDC; 180° crank angle corresponds to BDC.)

Figure 3 shows the computed oil transport in an identical geometry to the test engine. The red color signifies oil and the blue color signifies gas. The orange arrows on the right boundaries indicate the velocity of the liner, and the black arrows on the left indicate the instantaneous body acceleration. From 75° to 285° crank angle, the downward body force obviously drives oil on the piston third land to the bottom. However, it is not able to drain oil from the scraper ring step. After 285° crank angle, the body acceleration becomes upward. As a result, the oil trapped in the step moves upward. The oil distribution at the top right corner at 360° crank angle indicates that the trapped oil has reached the liner by TDC. Thus, bridging occurs in this condition. The body acceleration is not sufficient to drive oil on the piston third land to the top by TDC. Thus, at low engine speeds, bridging does not require any oil supply from the piston third land. It entirely results from the trapped oil. This observation can be justified by 2D-LIF experiments.

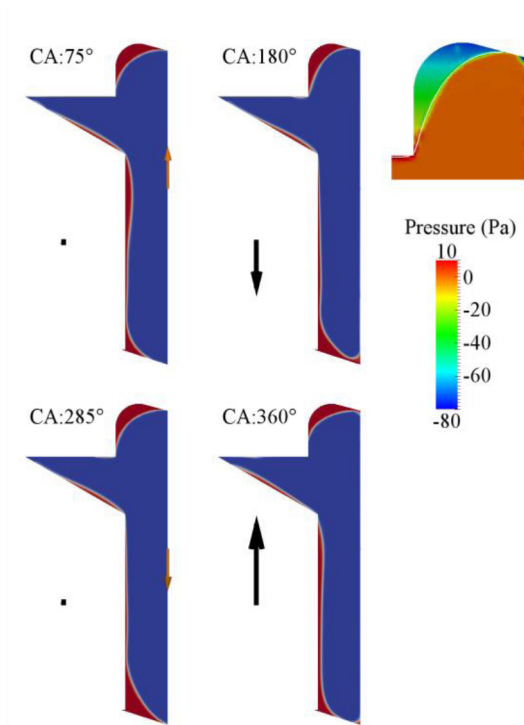


Figure 3. Computational simulation of oil transport in radial cross section at 800rpm with identical design to the test engine.

When the body acceleration is downward, the surface of the trapped oil appears “pinned” at the lower edge of the scraper ring step. This is because the tangent line of the solid surface is ambiguous at the sharp edge. As a result, the contact angle between the oil-gas interface and the solid surface is not well defined. When the body force drives oil in the step downward, it would first increase the angle formed by the oil-gas interface and the vertical inner solid surface before draining oil to the piston third land. Thus, oil can be trapped in the scraper ring step.

While the pinning effect can prevent oil from escaping a step, there must be an upward force to balance the downward body force in the bulk of the trapped oil. Figure 3 also shows the pressure distribution in the trapped oil at BDC. The white curve signifies the oil-gas interface, and the colors signify pressure. The pressure fields are approximately hydrostatic in the trapped oil. This is caused by surface tension. Wherever there is a curvature in the oil-gas interface, surface tension will generate a pressure difference in the oil and in the gas. If the gas pressure is approximately constant, a roughly linear variation in the interface curvature can result in a hydrostatic pressure field, which balances the downward body force.

In another type of configuration where the chamfer on the top of a piston third land is smaller or conforms to the step on the scraper ring, similar oil transport was observed. Figure 4 shows the computed oil transport at 800rpm with a rectangular scraper ring step and a conforming third land chamfer. With this design, the oil surface is pinned at the outer edge of the third land chamfer. As a result, oil is trapped in the step. However, in this simulation, the oil supplied to the scraper ring step was not sufficient to arise bridging.

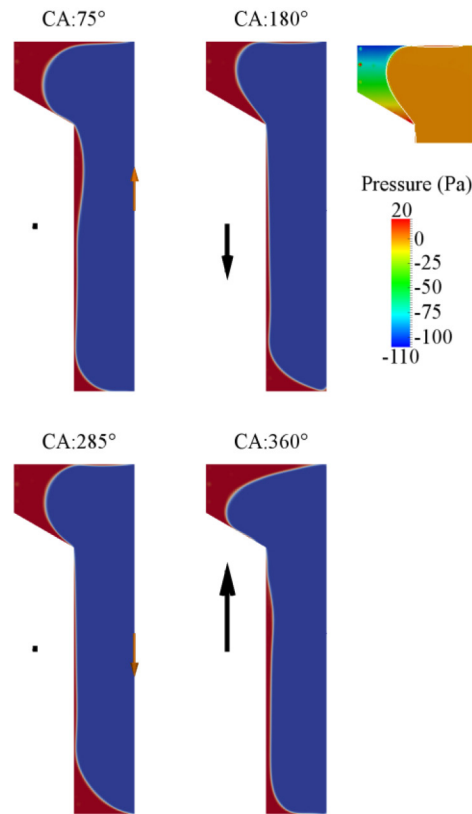


Figure 4. Computational simulation of oil transport in radial cross section at 800rpm with rectangular scraper ring step and conforming third land chamfer.

If more oil is supplied to a scraper ring step, the oil can overcome the pinning effect at the edge and be drained to the piston third land by BDC, as is shown in Figure 5. However, the sharp edge significantly restricts the thickness of the oil passage near it. As a result, the draining rate is limited and oil is still effectively trapped. With this increased oil supply to the scraper ring step, bridging occurs.

Figure 4 and Figure 5 both show the pressure distribution in the trapped oil at BDC. Hydrostatic pressure distributions are still present, except for minor gas bubbles.

Computational simulations revealed that oil can be trapped in a scraper ring step at an engine speed as low as 800rpm. It results from the sharp edge of a scraper ring step and the balance between surface tension and downward body acceleration. The trapped oil can result in bridging all by itself, though not necessary.

In contrast, oil trapping is not substantial at higher engine speeds. Figure 6 shows the oil distribution at 135° crank angle at 2500 rpm with the same scraper ring step. Only a slight quantity of oil can stick to the solid surface of a scraper ring step. It actually results from the viscous effect instead of surface tension, which can be supported by the modelling results to be shown. It indicates that oil trapping is evident only when body acceleration is sufficiently weak so that surface tension is able to balance it.

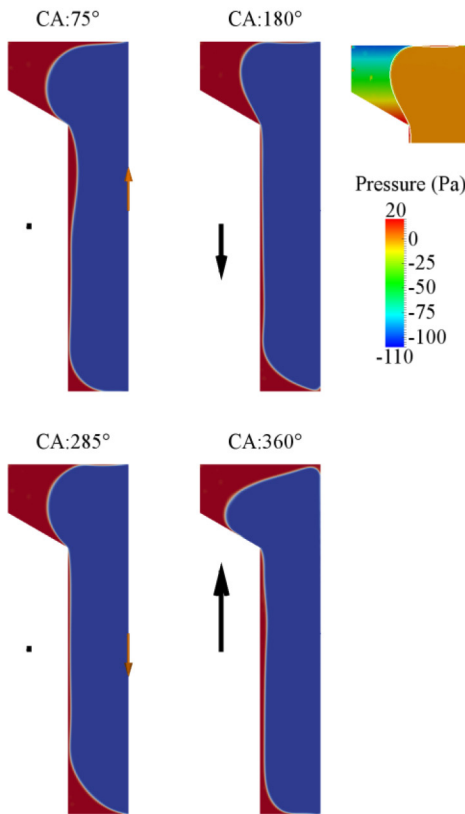


Figure 5. Computational simulation of oil transport in radial cross section at 800rpm with rectangular scraper ring step and conforming third land chamfer, with increased quantity of trapped oil.

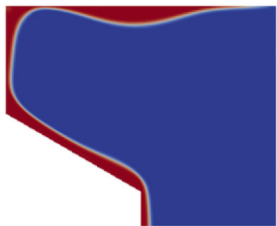


Figure 6. Oil distribution in the same rectangular scraper ring step at 135° crank angle at 2500rpm.

MODELING

In this section, a theoretical modeling of oil trapping and low-speed bridging will be demonstrated. The formulation will be presented with the trapping model only. The same formulation can be applied to the low-speed bridging model.

Oil Trapping

Critical Speed for Oil Trapping

Simulations indicated that significant quantity of oil can be trapped at low speeds, while only a slight quantity of oil sticks to a scraper ring step at high speeds. One can therefore expect a critical engine speed, which is the maximum speed at which significant quantity of oil can

be trapped and the minimum speed at which oil can hardly be trapped. A theoretical model was developed in order to evaluate this critical speed.

If the critical speed is less than the idle speed of an engine, oil trapping can be avoided in engine operations. Thus, approaches to reducing the critical speed are expected from the modeling.

A practical definition of the critical speed can be vague, since no oil can reside in a scraper ring step at no speed. In the model to be demonstrated, the critical speed for oil trapping is defined as the maximum speed at which a continuous oil-gas interface connecting the bottom edge and the upper surface of a scraper ring step can be maintained. An example of oil trapping is illustrated in Figure 7(a). In contrast, if an oil surface breaks up as shown in Figure 7(b), simulations indicated that the quantity of “trapped” oil would be very small and is usually insufficient to support low-speed bridging. Thus, the latter case would not be considered as oil trapping in the model.

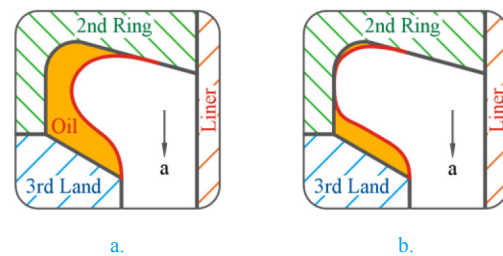


Figure 7. Definition of oil trapping in the model. ((a): oil trapping; (b) not oil trapping)

As implied in the foregoing section, the chamfer on the top of a piston third land may conform to the step of the scraper ring (Figure 8(a)), be smaller than the step (Figure 8(b)), or be larger than the step (Figure 8(c)). Although the experimental results were obtained with the third configuration, the development of the model will be demonstrated with the first two. The same modeling approach can be applied to the third configuration. It turned out that the critical speed with the third design is generally larger. Furthermore, the wedge labeled by the shaded region in Figure 8(c) constitutes an oil reservoir for the second ring groove, which could possibly increase oil consumption.

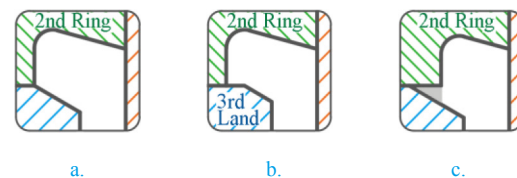


Figure 8. Geometric configurations of step in scraper ring and chamfer on piston third land.

Formulations

Computational simulations indicated that the primary force balance in trapped oil is between surface tension and body acceleration. Mathematically, it is described by the Young Laplace Equation:

$$p_0 - \rho a_x = \sigma \cdot \frac{-h_{xx}}{(1+h_x^2)^{3/2}}$$