Numerical Analysis of Internal Flow in the Clearance Gap of a Micro Swing Engine Postprint

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Abstract

This study employs a discrete velocity direction model to conduct a numerical investigation of microscale gas flow within the gap between the swing arm and cavity of a micro swing engine, analyzing the influence of arm motion on gas flow resistance and flow rate under pressure-driven conditions, and exploring the effects of gas rarefaction. The results indicate that when the arm motion direction coincides with the pressure drop direction, velocity slip induced by rarefied gas effects dominates the variation in flow rate relative to gas flow resistance; when the arm motion direction is opposite to the pressure drop direction, enhanced wall effects at the microscale lead to gas backflow near the boundaries and vortex structures at the flow inlet and outlet.

Full Text

Numerical Analysis of Clearance Gap Flow in a Micro Swing Engine

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Abstract

Numerical simulations of clearance gap flows between the swing arm and engine body in a Micro Internal Combustion Swing Engine were performed using the Discrete Velocity Direction (DVD) model. This study investigated the influence of swing arm movement on gas flow resistance and mass flux driven by differential pressure within the gap, and examined the effects of gas rarefaction. The results demonstrate that when the swing arm moves in the same direction as the pressure drop, velocity slip induced by rarefaction effects dominates changes in gas flow resistance and mass flux. Conversely, when the swing arm moves opposite to the pressure drop direction, enhanced wall effects at the microscale cause gas recirculation near the boundaries and vortex formation at the flow inlet and outlet.

Keywords: clearance gap flow; Discrete Velocity Direction model; rarefaction effect

0 Introduction

With advances in technology, electronic and mechanical products are trending toward miniaturization, placing higher demands on power supply units. The micro swing engine has become one of the most promising micro power systems due to its simple structure and high efficiency. However, reduced system scale leads to increased friction and leakage losses between moving and stationary components. During normal engine operation, the clearance gap is controlled at the micron scale, resulting in a gas Knudsen number between 0.01 and 1 within the gap—placing the flow in the slip or even transition regime where rarefaction effects are significant. Even with second-order or higher slip boundary conditions, the Navier-Stokes equations based on the continuum hypothesis can only be extended to flows with Kn < 0.5, and with substantial error [1, 2].

Previous researchers have investigated friction losses and leakage in micro swing engine clearances. Gu assumed continuum flow in the gap and used Navier-Stokes equations to estimate leakage and friction resistance [3]. Wang et al. approximated the gap flow as Bernoulli flow and estimated resistance losses using pipe flow calculations [4]. Guo et al. simulated gap flows using FLUENT software [5]. Analysis of these studies reveals that most research on gas flow resistance and leakage in micro swing engine clearances has employed Navier-Stokes-based methods for rough estimation, rarely considering rarefaction effects in microscale gas flows. However, microscale flow characteristics such as velocity slip and enhanced compressibility significantly affect engine aerodynamic performance.

This study employs a higher-accuracy kinetic method—the Discrete Velocity Direction (DVD) model [6, 7]—to investigate aerodynamic characteristics in micro swing engine clearances. Considering rarefaction effects in microscale gas flows, we examine how swing arm movement and gas rarefaction influence flow resistance and mass flux in micro-clearances, providing references for improving micro swing engine design and aerodynamic efficiency.

1 Discrete Velocity Direction Model

1.1 Introduction to the DVD Model

The Discrete Velocity Direction (DVD) model is a kinetic method that simplifies the Boltzmann equation by reducing its dimensionality to decrease computational cost. The DVD model maintains continuous molecular speed while discretizing molecular motion directions. It replaces the continuous velocity distribution space in the Boltzmann equation with discrete velocity directions, reducing the six-dimensional Boltzmann equation to three dimensions and thereby significantly decreasing computational requirements for numerical solution.

1.2 Model Validation

Gas flow between the swing arm and cylinder in a swing engine can be approximated as a combination of Couette and Poiseuille flows. Model accuracy was validated separately for these two flow types by comparing numerical results with the Linearized Boltzmann Equation (LBE) method. In the calculations, eight discrete velocity magnitudes were uniformly selected, with 84$×$4 discrete velocity directions. Using the molecular number density k_n in each velocity interval as the control variable, the governing equation for the DVD model can be derived.

For Couette flow, the computed dimensionless shear stress compared with LBE results [8] is shown in [Figure 1: see original paper]. For Poiseuille flow, the computed dimensionless mass flux compared with LBE results [9] is shown in [Figure 2: see original paper]. As shown in [Figure 1: see original paper] and [Figure 2: see original paper], from the slip flow to transition flow regimes, the maximum error between DVD model results and LBE method for both dimensionless shear stress and mass flux does not exceed 3.2%, demonstrating significantly higher accuracy than Navier-Stokes equations with slip boundary conditions.

2 Gas Flow in the Clearance Gap of a Micro Swing Engine

Within the clearance between the swing arm and cylinder of a micro swing engine, the gas flow belongs to the Couette-Poiseuille type due to simultaneous arm movement and pressure difference. High-temperature combustion gas enters the clearance gap. For a clearance size of 5 m, the Knudsen number can reach approximately 0.1, and further reduction in clearance size leads to the transition flow regime. This section investigates the effects of swing arm movement and gas rarefaction on flow resistance and mass flux. Argon gas was used for calculations with initial pressure at standard atmospheric pressure (101,325 Pa) and temperature at 273.15 K.

2.1 Influence of Swing Arm Movement on Gas Flow Resistance and Mass Flux

By varying the swing arm movement direction and velocity, the resulting variations in gas mass flux and flow resistance within the clearance are shown in [Figure 3: see original paper] and [Figure 4: see original paper], respectively. As indicated in these figures, at a given Knudsen number, the gas flow resistance increases with swing arm velocity regardless of movement direction, showing that pressure difference has minimal effect on flow resistance. At constant arm velocity, flow resistance increases with Knudsen number due to larger velocity gradients within the clearance.

When the swing arm moves in the same direction as the pressure drop (forward motion), gas mass flux increases with arm velocity. When moving in the opposite direction (reverse motion), mass flux first decreases, then increases with arm velocity. The reasons for these variations can be understood from streamline patterns within the clearance.

As shown in [Figure 5: see original paper]–[Figure 8: see original paper], when the swing arm moves in reverse, gas recirculation appears near the wall region. At constant Knudsen number, the recirculation zone expands with increasing arm velocity. At constant arm velocity, the recirculation zone expands with increasing Knudsen number. At Kn = 0.1128, the recirculation zone expands into the main flow region, with distinct vortex structures appearing at the flow inlet and outlet. At this condition, the driving effects of wall motion and pressure difference on gas flow are nearly equal. At Kn = 0.3385, the entire gas flow reverses direction, indicating that wall effects have extended throughout the entire flow field, and clearance leakage is primarily determined by swing arm velocity. These results demonstrate that for gas flow in micro swing engine clearances, the characteristic scale determines the dominant mechanism controlling clearance leakage.

2.2 Influence of Rarefaction on Dimensionless Flow Resistance and Mass Flux

By varying the gas flow Knudsen number, the variations in dimensionless mass flux and flow resistance are shown in [Figure 9: see original paper] and [Figure 10: see original paper], respectively. As shown in [Figure 9: see original paper], when the swing arm moves forward, dimensionless mass flux decreases with increasing gas rarefaction due to rapidly decreasing gas velocity at the centerline. As shown in [Figure 10: see original paper], dimensionless flow resistance increases with gas rarefaction, while swing arm velocity and direction have minimal effect on flow resistance.

Conclusion

This study employed the Discrete Velocity Direction model to investigate microscale gas flow in the clearance between the swing arm and cylinder of a micro swing engine, examining the effects of gas rarefaction and swing arm movement on flow resistance and mass flux driven by pressure difference. The main conclusions are:

1. When the swing arm moves in the same direction as the pressure drop, gas mass flux increases with swing arm velocity.
2. When the swing arm moves opposite to the pressure drop direction, gas mass flux first decreases then increases with swing arm velocity, with re-

circulation zones and vortex structures appearing near walls and at the inlet/outlet.
3. Regardless of swing arm movement direction relative to the pressure drop, gas flow resistance increases with swing arm velocity.

For rarefied gas flow in micro swing engine clearances, when the swing arm moves in the same direction as the pressure drop, arm velocity should be minimized to reduce gas leakage. When the swing arm moves opposite to the pressure drop direction, the optimal arm velocity should be determined by comprehensively considering the effects of both flow resistance and leakage on overall engine efficiency to improve system performance.

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