Numerical Analysis of Clearance Internal Flow in Micro Pendulum Engines (Postprint)

Authors: Sun Meng (1,2); Zhang Zhenyu (1); Kong Wenjun (1)

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Abstract

This study employs a discrete velocity direction model to conduct numerical investigations on microscale gas flow within the clearance between the swing arm and cavity of a micro pendulum engine, analyzing the influence of swing arm motion on gas flow resistance and flow rate under pressure-driven conditions, and investigating the effects of gas rarefaction. The results indicate that when the direction of swing arm motion coincides with the pressure drop direction, velocity slip caused by rarefied gas effects dominates over gas flow resistance in determining flow rate variations; when the swing arm motion direction is opposite to the pressure drop direction, enhanced wall effects at the microscale induce gas backflow near the boundaries, and vortex structures emerge at the gas flow inlet and outlet.

Full Text

Preamble

On Clearance Gap Flow in a Micro Internal Combustion Swing Engine

SUN Meng[1],[2], ZHANG Zhen-Yu[1], KONG Wen-Jun[1]
[1] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
[2] University of Chinese Academy of Sciences, Beijing 100039, China

Abstract

This paper presents a numerical investigation of microscale gas flow within the clearance gap between the swing arm and engine body of a micro internal combustion swing engine using the Discrete Velocity Direction (DVD) model. The study analyzes the influence of swing arm motion on gas flow resistance and mass flux driven by pressure differential within the gap, and explores the effects of gas rarefaction. The findings reveal that when the swing arm moves in the same direction as the pressure drop, velocity slip caused by rarefied gas effects dominates the variation in mass flux relative to flow resistance. When the swing arm moves opposite to the pressure drop direction, gas recirculation occurs near the boundaries due to enhanced wall effects at microscale, with vortex structures emerging at the flow inlet and outlet.

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

0 Introduction

With technological advancement, 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 energy 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 Knudsen numbers between 0.01 and 1 within the gap. This places the gas flow in the slip flow or even transition flow regime, where rarefied gas effects become significant. Even with second-order or higher-order slip boundary conditions, the Navier-Stokes equations—applicable to continuum models—can only be extended to flow regimes with $\mathrm{Kn} < 0.5$, and with substantial errors [1, 2].

Previous researchers have investigated friction losses and leakage in micro swing engine clearances. Gu assumed continuous flow within 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 employed pipe flow calculations to estimate resistance losses [4]. Guo et al. simulated gap flow 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 equation methods for rough estimation, rarely considering rarefaction effects in microscale gas flow. However, microscale flow characteristics such as velocity slip and enhanced compressibility significantly influence engine aerodynamic performance.

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

1.1 Discrete Velocity Direction 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 of a swing engine can be approximated as a combination of Couette flow and Poiseuille flow. We validated the model accuracy in both flow configurations by comparing numerical results with those from the Linearized Boltzmann Equation (LBE) method. In the calculations, eight discrete speed values were uniformly selected, with 84 discrete velocity directions. Using the molecular number density in each speed interval (kn) as the control equation variable, the governing equation for the DVD model was obtained.

1.2.1 Couette Flow

The dimensionless shear stress calculated by the DVD model was compared with LBE results [8] as shown in [Figure 1: see original paper].

1.2.2 Poiseuille Flow

The dimensionless mass flux calculated by the DVD model was compared with LBE results [9] as shown in [Figure 2: see original paper].

As shown in [Figure 1: see original paper] and [Figure 2: see original paper], from slip flow to transition flow regimes, the maximum error between DVD model calculations and LBE method results 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 Micro Swing Engine Clearance Gap

Within the clearance between the swing arm and cylinder of a micro swing engine, gas flow belongs to the Couette-Poiseuille flow category due to simultaneous swing arm motion and pressure differential. High-temperature combustion gas enters the clearance gap. For a clearance size of 5 m, the Knudsen number can reach approximately 0.1, entering the transition flow regime if the clearance further decreases. Using argon as the working fluid, calculations were performed with initial pressure at standard atmospheric pressure (101,325 Pa) and temperature at 273.15 K under pressure differential conditions.

2.1 Influence of Swing Arm Motion on Flow Resistance and Mass Flux

By varying the swing arm motion direction and speed, the variation curves of gas mass flux and flow resistance within the gap were obtained as shown in [Figure 3: see original paper] and [Figure 4: see original paper].

[Figure 3: see original paper] shows mass flux variation with swing arm velocity, while [Figure 4: see original paper] shows flow resistance variation with swing arm velocity. At constant Knudsen number, flow resistance increases with swing arm velocity regardless of motion direction, indicating minimal influence from pressure differential. At constant swing arm velocity, flow resistance increases with Knudsen number due to increased velocity gradients. When the swing arm moves in the forward direction (with the pressure drop), mass flux increases with swing arm velocity. When moving in the reverse direction (against the pressure drop), mass flux first decreases, then increases with swing arm velocity. The reasons for these variations can be observed from streamlines within the gap.

Streamline patterns for reverse swing arm motion at various Knudsen numbers and velocities are shown in [Figure 5: see original paper] through [Figure 8: see original paper]. When the swing arm moves opposite to the pressure drop direction, gas recirculation appears near the wall region. At constant Knudsen number, the recirculation zone expands with increasing swing arm velocity. At constant swing 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, wall motion and pressure differential exert nearly equal driving forces on the gas flow. At Kn = 0.3385, the entire gas flow reverses direction, indicating that wall effects have dominated 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 factor controlling leakage flow.

2.2 Influence of Rarefaction on Dimensionless Flow Resistance and Mass Flux

By varying the Knudsen number of the gas flow, the variation curves of dimensionless mass flux and flow resistance were obtained as shown in [Figure 9: see original paper] and [Figure 10: see original paper].

As shown in [Figure 9: see original paper], when the swing arm moves in the forward direction, dimensionless mass flux decreases with increasing rarefaction due to rapidly decreasing gas velocity at the center region. As shown in [Figure 10: see original paper], dimensionless flow resistance increases with rarefaction, while swing arm velocity and direction have minimal influence on flow resistance.

Conclusion

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

1. When swing arm motion direction aligns with the pressure drop direction, gas mass flux increases with swing arm velocity.
2. When swing arm motion direction opposes the pressure drop direction, gas mass flux first decreases then increases with swing arm velocity, with recirculation zones and vortex structures appearing near walls and at the inlet/outlet.
3. Regardless of whether swing arm motion direction aligns with the pressure drop, flow resistance increases with swing arm velocity.

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

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Note: Figure translations are in progress. See original paper for figures.