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Numerical analysis for irreversible processes in a piston-cylinder system

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ABSTRACT

A numerical analysis for the irreversible process in an adiabatic piston-cylinder system has been conducted. Axisymmetric compressible momentum and energy equations were solved numerically to obtain the state quantities of the system using the laminar flow model. The numerical method is based on the combined Implicit Continuous-fluid Eulerian technique and the Arbitrary-Lagrangian-Eulerian method. The computations were performed for a single compression process and a single expansion process with the piston velocities of ±1 m/s, ±2 m/s, ±4 m/s, ±6 m/s, ±8 m/s and ± 10 m/s and for cyclic compression and expansion processes with sinusoidal velocity variation. It is found that the piston velocity has effects on the state quantities of the piston-cylinder system and it experienced an irreversible process when the piston moved with an infinite velocity. However, the process can be treated as a polytropic process and the polytropic exponent is approximately equal to the adiabatic exponent, $n \approx \gamma$ when the piston velocity is less than ±10 m/s. In the cyclic process of 10,000 rpm, the internal energy increases 0.037% of the compression work in each cycle.

1. Introduction

Design of heat engines, energy devices in a power plant and thermo-fluid devices have increased the need for understanding of thermodynamics for the advance of energy and environmental technologies. A process of a compression or an expansion of a gas in a piston-cylinder system is common in many applications, however an irreversible process is not well understood [1–7]. In thermodynamics, state quantities at a final state in a reversible process can be determined. A reversible process may occur when a system is maintained continuously and thermally at an equilibrium state [7–10]. Therefore, the reversible process is also called a quasi-static or a quasi-equilibrium process [8]. The process is reversible when a piston moves with zero velocity in a piston-cylinder system. On the other hand, the thermal equilibrium state breaks in the system and the process becomes irreversible when the piston moves with infinite velocity. In general, we cannot determine the state quantities at a final state in an irreversible process [9]. The only exception is a throttling process when a gas or a steam passes through a capillary tube or a porous material. For example, in an adiabatic throttling process, the specific enthalpy at the final state is identical to the specific enthalpy at the initial state. Then, the state quantities at the final state can be determined. This strictly highlighted in a thermodynamic textbook [9] that we can make calculations only for a reversible process.

A process which occurs in an actual heat engine or a turbine is irreversible since a piston or a turbine blade is moving with infinite velocity. Therefore, in thermodynamics, state quantities at a final state in an adiabatic irreversible process for an open system is obtained assuming an adiabatic efficiency. However, the path of an adiabatic irreversible process is still indeterminate and cannot be drawn on a thermodynamic diagram (e.g. *p-v* diagram) [8]. Therefore, state quantities at a final state in an adiabatic irreversible process cannot be determined without the adiabatic efficiency. It is said that the irreversible process can be approximately treated by assuming a polytropic process with an appropriate exponent n [11]. Petrescu et al. summarized previous research results obtained from the kinetic theory on the thermodynamic processes of a piston-cylinder system with infinite piston velocity [12]. Their polytropic exponent n for an adiabatic irreversible process is a function of the piston velocity as

$$n = \left(1 \mp \frac{\gamma u_p}{\sqrt{\gamma R T}}\right)(\gamma - 1) + 1 \quad (-:\ \text{compression}, +:\ \text{expansion}) \tag{1}$$

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Nomenclature

C_v	constant volume specific heat, J/(kg K)
D	cylinder diameter, m
i	specific internal energy, J/kg
m	mass in cylinder, kg
n	polytropic index or, –
N	rotation number per minute, –
p	pressure, Pa
R	gas constant J/(kg K)
T	temperature, K
t	time, s
u, v	velocity components, m/s
u_p	piston velocity, m/s
v^*	specific volume, m^3/kg
V	volume of cylinder, m^3
r, x	coordinates, m
w	specific work, J/kg
ϕ	dissipation function Eq. (6)
γ	specific heat ratio, –
λ	thermal conductivity, W/(m K)
μ	viscosity, Pa s
θ	crank angle, rad or deg
ρ	density, kg/m^3
τ	shear stress, Pa

Sub/superscripts

ave	average
BDC	bottom dead center
f	final
i	initial
ps	piston surface
rev	reversible
TDC	top dead center

where u_p is the piston velocity, γ is the specific heat ratio, R is the gas constant and T is the average gas temperature in the cylinder. However, this polytropic exponent n is obtained under the situation that the piston is moving with constant velocity and the energy conversion from the kinetic energy to thermal energy is not considered after the piston stops. Rodrigues and Liburdy [13] experimentally investigated the effect of heat transfer from a cylinder wall of a piston-cylinder system during free expansion on the polytropic exponent n. However, the polytropic exponent n for the adiabatic case was not obtained. Understanding of reversible and irreversible processes is important for the advance of energy and environmental technologies. However, to date, there are no data available in the literature except [12] to obtain the value of n.

The heat and fluid flow in an actual internal combustion engine have been analyzed numerically by using the CFD codes, such as FLUENT, [14–16] or KIVA-3 [17,18], since the heat and fluid flows have a strong effect on the performance of the engine efficiency. So, state quantities in an irreversible process can be obtained by simply solving the momentum equation and energy equation which includes the substantial derivative of pressure and the viscous dissipation terms. However, a complete search of the literature revealed that there is no previous research which focuses on the irreversible process that occurs in a piston-cylinder system. This is the motivation of the present study to conduct numerical analysis for an irreversible process in a piston-cylinder system.

This study aims to investigate the state quantities for the irreversible process in the piston-cylinder system in order to understand the fundamentals of the irreversible process. If the velocity range in which the process can be considered is known in a reversible process, the assumption of reversible process can be applicable to an irreversible process with theoretical verification. The numerical analysis is conducted using the numerical method based on the combined technique of the Implicit Continuous-fluid Eulerian (ICE) technique and the Arbitrary Lagrangian Eulerian (ALE) method proposed by Amsden et al. [19]. The computations were performed for a single compression and a single expansion process with constant piston velocities. The computations were performed for cyclic compression and expansion processes with sinusoidal velocity variation.

2. Formulation

2.1. Description of the problem and conservation equations

The schematic diagram of the problem under consideration that assumes an insulated piston-cylinder system filled with an ideal gas is shown in Fig. 1. The analyses are based on the assumption of a single compression process, a single expansion process and a cyclic compression and expansion processes. The piston is located at the bottom dead center (BDC) at $t \leqslant 0$ and it begins to compress the gas with constant velocity at $t = 0$. Note that the constant piston velocity was used because we need to investigate the fundamentals of reversible and irreversible processes occur during a single compression and expansion processes. The pressure and temperature of the gas increase because of the compression work by the piston. The piston stops when it reaches at the top dead center (TDC). For the case of the expansion process, the piston is located at the TDC at $t \leqslant 0$. The piston travels with the constant velocity, u_p and it stops when it reaches at the BDC. For the case of cyclic compression and expansion processes, the piston travels with sinusoidal velocity variation. Compressible momentum and energy equations are solved numerically to obtain the pressure and temperature of the gas during the compression or expansion processes. The flow is assumed to be axisymmetric and laminar. The thermo physical properties of the fluid except the density are assumed to be constant. The governing equations can be expressed as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{1}{r}\frac{\partial \rho r v}{\partial r} = 0 \quad (2)$$

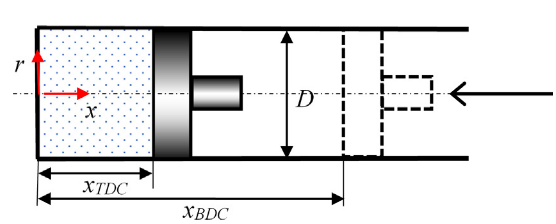

Fig. 1. The schematic diagram of problem.