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Experimental study on two-phase adiabatic expansion in a reciprocating expander with intake and exhaust processes

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ABSTRACT

In the present study, visualization and measurement of two-phase adiabatic expansion in a reciprocating cylinder with intake and exhaust processes is carried out. Experimental setup with piston and cylinder which mimics reciprocating expander was constructed and boiling phenomenon is visualized. Working fluids are water and ethanol, and their inlet temperatures are 100 and 80 °C, respectively. The piston and cylinder are made of polycarbonate with diameter of $D_p = 55$ mm. The inner pressure is measured by the pressure sensor embedded in the piston. Indicated work and indicated adiabatic efficiency are calculated from the P–V diagram. The effects of heat capacity loss from the working fluid to the inner wall and the remained liquid, injection loss and non-equilibrium loss are evaluated. Evaporated gas velocity at the interface is calculated from the volume and density of the vapor phase, which is found to be almost proportional to the piston velocity. The adiabatic efficiency increases with the piston velocity due to the reduction of heat capacity loss. When the maximum piston velocity exceeds 300 mm/s, the effect of heat capacity loss becomes negligible. Measured indicated adiabatic efficiency of water is about 86% at maximum piston velocity of $v_{p,max} = 380$ mm/s, while that of ethanol is about 82% for the same condition.

1. Introduction

In recent years, waste heat recovery systems from moderate to low temperature heat sources such as organic Rankine cycles (ORCs) are attracting large attentions and have been widely investigated in order to improve the energy utilization efficiency. Among them, trilateral cycle has a potential of achieving high exergy recovery efficiency [1–5]. In the trilateral cycle, working fluid is pressurized and kept as a single liquid phase during the heating process. Heat is transferred from the heat source to the single phase working fluid, which results in low exergy loss during the heat exchange process due to excellent temperature profile matching. Therefore, exergy efficiency of the trilateral cycle can be theoretically the highest among other heat cycles when the heat source temperature descends during the heat exchange process. On the other hand, in the expansion process of the trilateral cycle, working fluid is introduced as a liquid and then flashed to liquid–vapor two-phase. This two-phase expander is one of the key components to realize the trilateral cycle system.

For two-phase expansion or wet-vapor expansion, the volumetric expander is preferable from the viewpoint of erosion durability. There are several studies on wet-vapor expansion for Lysholm turbine expander. Smith et al. [6–8] estimated the performance and cost of trilateral flash cycle using Lysholm twin screw turbine. They reported that the adiabatic efficiency of the expander can reach 70%, and that the trilateral flash cycle can produce 1.8 times larger output power than the simple Rankine cycle from hot steam of 100–200 °C. Ohman et al. [9] investigated Lysholm turbine and reported that peak efficiency is sensitive to the inlet vapor condition, and that further investigation for the inlet two phase condition is needed. Oreijah et al. [10] conducted an experimental study to compare trilateral flash cycle and ORC using screw expanders. They reported that the trilateral cycle shows a larger power generation than conventional ORCs, but the expander can be operated at lower rotational speed in the ORCs than in the trilateral cycle.

When using the heat source of moderate temperature, the expansion ratio becomes very large in the expansion process of the trilateral cycle [1,2]. To overcome this difficulty, a reciprocating expander should be a preferable choice since it can be designed for large expansion ratio conditions. Steffen et al. [11] proposed a novel trilateral cycle using cyclone separation and reciprocating expander, and simulated the influence of injection timing, material

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Nomenclature

c_p	liquid heat capacity [kJ/(kg·K)]
D	diameter [mm]
E	energy [kJ]
g	gravity acceleration [m/s^2]
h	heat transfer coefficient [W/(m^2·K))
l_v	latent heat [kJ/kg]
m	mass [kg]
p	pressure [MPa]
Q	heat [kJ]
t	time [s]
S	interface area [m^2]
T	temperature [°C, K]
u	specific internal energy [kJ/kg]
v	velocity [mm/s]
V	volume [m^3]
W	work [kJ]
z	piston displacement [mm]

Greek symbols

α	acceleration [mm/s^2]
ε	ratio
Δ	difference
λ	thermal conductivity [W/(m·K)]
μ	viscosity [Pa·s]
ρ	density [kg/m^3]
σ	surface tension [mN/m]
η	efficiency [%]
ζ	loss ratio [%]

Subscripts

0	initial condition
ad	adiabatic
ave	average
b	bubble
cut	cut-off
cyl	cylinder
exp	expansion
fl	working fluid
hc	heat capacity
inj	injection
inter	interface
ise	isentropic (quasi-static)
liq	liquid
loss	loss
max	maximum
NE	non-equilibrium
p	piston
sat	saturate
sus	bottom stainless plate
vap	vapor
vol	volume
–	difference

Superscript

*	dimensionless quantity

of cyclone, the size and frequency of the reciprocating expander. They concluded that effective thermal insulation of the cyclone wall is important, and found that large stroke volume and engine speed decrease the isentropic efficiency of the expander due to the influence of injection timing. They also reported that the cycle using water as a working fluid has 1.35–1.7 times higher exergy efficiency than the ORCs ever studied. Bao et al. [12] reviewed the working fluids and capacities, costs and advantages of different expander types, and reported that reciprocating piston expander has wide adaptability for variable working conditions and tolerance for two-phase expansion.

A two-phase expansion in adiabatic condition is called as flash evaporation. Flash evaporation phenomenon has been studied in the field of refrigeration, desalination, nuclear reactor, jet nozzle or other chemical processes. Yan et al. [13] and Zhang et al. [14] carried out experiments on static and circulatory flash evaporation and investigated the steam-carrying effect. Saury et al. [15] studied flash evaporation of water film and proposed a correlation between the dimensionless maximum mass flow rate, dimensionless initial temperature, depressurization rate, superheat and initial water height. Mutair et al. [16] conducted an experimental study on flash evaporation from a superheated water jet. They concluded that the inflection point and evaporation end heights can be normalized with the nozzle diameter, and can be correlated with Weber, Froude and Jacob numbers.

The above flash evaporation studies were carried out in a flash chamber, but did not focus on the output work which could be taken out from the system. Therefore, further investigations on two-phase adiabatic expansion to increase output power and to improve adiabatic efficiency are needed. In the actual reciprocating expander, expansion process is divided into three major processes, i.e. intake, expansion and exhaust. In the intake process, hot working fluid is introduced into the cold cylinder which is cooled during the preceding expansion cycle. If the cold liquid remains after the exhaust process, this may also cool the hot inlet liquid. Such heat capacity loss deteriorates adiabatic efficiency. On the other hand, remained bubbles may effectively induce initial phase change. Therefore, two-phase expansion experiments including intake and exhaust processes should be conducted, and the effects such as heat capacity loss and initiation of phase change should be evaluated.

In the present study, working fluid is expanded in a thermally insulated cylinder to investigate the basic characteristics of two-phase adiabatic expansion in a reciprocating expander with intake, expansion and exhaust processes. Boiling phenomenon is visualized by the high speed micro scope. The working fluid and the setup are warmed up before the expansion experiment to exclude the effect of heat dissipation loss to the atmosphere. A pressure sensor and a thermo-couple are embedded in the piston to measure vapor pressure and temperature inside the cylinder. The indicated output power and adiabatic efficiency are obtained from the measured *P*–*V* diagram. The effects of three loss mechanisms, i.e. heat capacity loss, non-equilibrium loss and injection loss are evaluated.

2. Experimental setup and procedure

2.1. Experimental setup

Fig. 1 shows the schematic of the experimental setup. The cylinder is a double pipe made of polycarbonate. The piston with diameter of D_p = 55 mm is also made of polycarbonate. The bottom of the cylinder is made of thin stainless plate with thickness of 0.8 mm. Mechanisms to introduce hot working fluid into the cylinder and to exhaust cold two phase flow are added to the original setup for the two-phase experiment in the previous study [17].