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Experimental and modeling study on adiabatic two-phase expansion in a cylinder

Hiroshi Kanno [a,*], Naoki Shikazono [b]

[a] Railway Technical Research Institute, 2-8-38 Hikari-cho, Kokubunji-shi, Tokyo, Japan
[b] The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, Japan

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ABSTRACT

In the present study, visualization and measurement of two-phase adiabatic expansion in a cylinder with moving piston are carried out. Experimental setup with piston and cylinder which mimics reciprocating expander was constructed and boiling phenomenon is visualized. The difference between measured and quasi-static pressures becomes larger as piston velocity is increased. With the decrease of piston diameter, agitation of the liquid phase becomes stronger and adiabatic efficiency becomes closer to that of the quasi-static state. The adiabatic efficiency is almost independent on the initial fluid temperature. Finally, a model to predict pressure change in two-phase expansion process is proposed and the model can predict adiabatic efficiency within the range of about ±2.5% accuracy. From the model prediction, it is shown that the uniformity of the liquid phase temperature distribution is the key factor for improving the adiabatic efficiency.

1. Introduction

In recent years, waste heat recovery systems using heat cycles have been widely investigated in order to improve the energy utilization efficiency. To convert moderate or low temperature heat into power, trilateral cycle [1–4] attracts large attentions because of its high potential of exergy recovery. In the trilateral cycle, working fluid is pressurized and kept as a single liquid phase during the heating process. Temperature profile matching can be improved during the heat exchange between heat source and liquid phase working fluid, which results in the exergy loss reduction. Therefore, exergy efficiency of the trilateral cycle can be theoretically the highest among other heat cycles. In the expansion process of the trilateral cycle, working fluid is flashed and becomes 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 view point of erosion durability. There are several studies of wet-vapor expansion such as Lysholm turbine, scroll or reciprocating expanders [5–11]. Ohman et al. [5] 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. Bao et al. [7] reviewed the working fluids and the capacity, cost, advantages of several kinds of expanders, and reported that reciprocating piston expander has the advantage of adaptability for variable working conditions and tolerance for two-phase expansion. Smith et al. [8–10] 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 simple Rankine cycle for hot steam of 100–200 °C. Oreijah et al. [11] 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 ORC, but the expander can be operated at lower rotational speed in ORC than in trilateral cycle. Steffen et al. [12] proposed a novel trilateral cycle using cyclone separation and reciprocating expander, and simulated the influence of injection timing, material of cyclone, the size and frequency of 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 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.

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. [13,14] conducted an experimental study on static and circulatory flash evaporation

* Corresponding author.

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Nomenclature

Bo	Bond number
c_p	liquid heat capacity (kJ/kg K)
d	constant value
D	diameter (mm)
g	gravity acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
Ja	Jakob number
l_v	latent heat (kJ/kg)
m	mass (kg)
n	coefficient
p	pressure (MPa)
Q	heat (kJ)
r	ratio
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)

Greek symbols

a	acceleration (mm/s^2)
β	agitation factor
Δ	difference
λ	thermal conductivity (W/m K)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (mN/m)

η	efficiency (%)

Subscripts

0	initial condition
1,2,3	number of coefficient
agi	agitated
ave	average
b	bubble
cyl	cylinder
eff	effective
eq	equilibrium
exp	expansion
fl	working fluid
gen	generated
inter	interface
ise	isentropic(quasi-static)
liq	liquid
max	maximum
p	piston
sat	saturate
sus	bottom stainless plate
total	total
vap	vapor
–	difference

Superscripts

*	dimensionless quantity
′	previous time step

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.

All the above flash evaporation studies were carried out with the flash chamber i.e. in a constant volume condition without taking out work from the system. Thus, research on adiabatic two-phase expansion to generate output power in an expander is still limited. Especially, the mechanism of adiabatic efficiency reduction in two-phase expansion is not fully investigated. Most of the studies on flash "evaporation" deal with the depressurization rate as an input parameter by controlling the pressure of vacuum tank and evaluate the influence of the depressurization rate against time [14,15]. However, when obtaining work from flash "expansion", the inner pressure should be kept as high as possible, i.e. it is desirable to keep the depressurization rate as low as possible. In addition, the influence of expansion velocity on the pressure degradation is of interest. In this study, working fluid is expanded and work is generated by the piston in a thermally insulated cylinder. Boiling is visualized by the high speed micro scope. Output power is obtained from the measured P–V diagram. Adiabatic efficiency is evaluated and the effects of piston velocity and piston diameter are evaluated. Finally, a model to predict pressure change in a two-phase expansion process is proposed. To simplify the phenomena, one dimensional thermal conduction model is used and the temperature distribution in the cylinder is calculated. The agitation effect of boiling on adiabatic efficiency is also investigated.

2. Experimental setup and procedure

2.1. Experimental setup

Fig. 1 shows the insulated cylinder for two-phase expansion experiment. In this study, water is used as the working fluid. The cylinder is a double pipe made of polycarbonate. The bottom of the cylinder is made of thin stainless plate with thickness of 0.6 mm. The working fluid and the setup are heated up to operating temperature by hot air, and then the double tube is vacuumed by a vacuum pump for thermal insulation before the expansion experiment. The temperature of liquid and vapor phases are

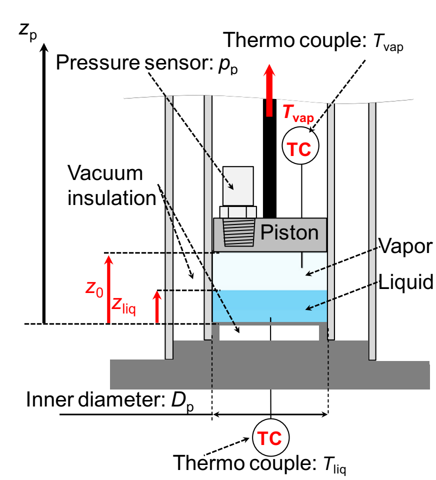

Fig. 1. Cross section of the cylinder and the piston.