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Modeling study on two-phase adiabatic expansion in a reciprocating expander

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ABSTRACT

In the present study, modeling of two-phase adiabatic expansion in a reciprocating cylinder is proposed. Experimental data obtained from the setup with piston and cylinder which mimics reciprocating expander were used for model validation. From the experiment, it is recognized that mixing of the liquid due to boiling bubbles has a strong impact on pressure change during adiabatic expansion. Therefore, two phase adiabatic vaporization in a cylinder is considered to be mainly dominated by the heat transfer between the bulk liquid and the gas–liquid interface. Experimental correlation for the Nusselt number based on Prandtl, Reynolds and Bond numbers is proposed. Pressure change and indicated adiabatic efficiency in adiabatic two phase expansion are calculated by solving the energy balance equations using the proposed Nusselt number correlation. The present model can reproduce the pressure-change and the indicated adiabatic efficiency in adiabatic two phase expansion within about 5% accuracy.

1. Introduction

In recent years, wet vapor expansion and two-phase expansion are attracting large attentions in waste heat recovery systems from low to moderate temperature heat sources. In this field, organic Rankine cycles (ORCs) and trilateral cycle have been studied in order to improve the energy utilization efficiency [1–5]. By keeping the working fluid as a single liquid phase in the heat exchange process, the temperature profile matching between the working fluid and heat source is drastically improved, which results in low exergy loss of the cycle. Therefore, exergy efficiency of the trilateral cycle can be theoretically the highest among the other heat cycles when the heat source temperature descends during the heat exchange process. In the trilateral cycle, two phase expander is the key component of the system. From the view point of erosion durability, the volumetric expander is preferable to attain high reliability. It is very important to clarify the two-phase expansion phenomenon for the development of efficient and reliable two-phase expander.

To evaluate the potential of the trilateral cycle, knowledge on two phase expansion is indispensable. There are several experimental studies on wet-vapor expansion for Lysholm turbine expander. Smith et al. [6–8] estimated the performance and the cost of trilateral flash cycle using Lysholm twin screw turbine. Oreijah et al. [9] conducted an experimental study to compare trilateral flash cycle and ORC using screw expanders. They reported that the trilateral cycle has a potential for reaching larger thermal efficiency than conventional ORCs. Ohman et al. [10] investigated Lysholm turbine and reported that peak efficiency is sensitive to the inlet vapor condition. They also proposed an empirical correlation for the adiabatic efficiency, which assumes a linear relationship between vapor fraction and adiabatic efficiency [11].

When using a heat source of moderate temperature, the expansion ratio becomes very large in 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. Bao et al. [12] reviewed the characteristics of different types of expenders. They evaluated the capacities, costs and advantages, and mentioned that the reciprocating piston expander has wide adaptability for variable working conditions and tolerance for two-phase expansion. Studies on two-phase expansion phenomenon in a cylinder (constant-volume chamber) are reported as flash expansion experiments 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

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Nomenclature

Bo	Bond number
c	heat capacity [kJ/(kg·K)], coefficient
c_p	liquid heat capacity [kJ/(kg·K)]
d	diameter [mm]
D	piston diameter [mm]
E	energy [kJ]
g	gravity acceleration [m/s^2]
h	heat transfer coefficient [W/(m^2·K))
Ja	Jacob number
L	latent heat [kJ/kg]
m	mass [kg]
Nu	Nusselt number
p	pressure [MPa]
Pr	Prandtl number
Q	heat [kJ]
Re	Reynolds number
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

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

Subscripts

0	initial condition
ad	adiabatic
b	bubble
cut	cut-off
cyl	cylinder
exp	expansion
fl	working fluid
gen	generated
heat	heat capacity
inj	injection(measured in inlet valve)
int	interface
ise	isentropic (quasi-static)
Lap	laplace
l	liquid
loss	loss
p	piston
sat	saturation
SUS	bottom stainless plate
v	vapor
vol	volume

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.

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. Studies on the pressure change and adiabatic efficiency in two-phase expansion are still limited, so further investigations on two-phase adiabatic expansion to increase output power and to improve adiabatic efficiency are needed. Especially, to clarify the phenomenon, modeling study on adiabatic two-phase expansion should be conducted. As intake and exhaust valves are located closely in the reciprocating expander, the hot liquid is introduced into the cold cylinder wall, which results in the heat capacity loss from the working fluid. Steffen et al. [16] simulated the performance of trilateral cycle using a reciprocating expander with cyclone separator, in which the saturated liquid working fluid is separated into liquid and vapor, and only vapor phase is introduced into the cylinder. They also evaluated the material of cyclone and reported that the effective thermal insulation of the cyclone wall is important. Therefore, thermal insulation or heat transfer from the working fluid to the cylinder wall will become important for the modeling study on the two-phase adiabatic expansion phenomenon.

In the present study, modeling of phase-change on the liquid–vapor interface in a reciprocating cylinder is proposed using our previous experimental results [17,18]. An experimental correlation for the Nusselt number based on Prandtl, Reynolds and Bond numbers is proposed. Using the correlation, a model which can predict pressure change and indicated adiabatic efficiency during adiabatic two-phase expansion is developed.

2. Heat transfer phenomena in two-phase expansion

2.1. Experimental setup

Experimental setup is the same as our previous study [17,18]. 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.

In the experiment without intake and exhaust process, degassed working fluid is introduced into the cylinder, and 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 measured by thermocouples attached to the piston and the bottom of the cylinder. The pressure in the cylinder is measured by the pressure sensor embedded in the piston. Indicated work is obtained from a *P–V* diagram.

In the experiment with intake and exhaust valves, water and ethanol are used as the working fluids, and their inlet temperatures T_{inj} are 100 °C and 80 °C, respectively. In this setup, intake and exhaust valves are located at the bottom plate, so the bottom plate is cooled by the remained working fluid after the preceding exhaust process. In the subsequent expansion process, the introduced hot working fluid is cooled by the bottom plate. This heat capacity loss is not observed in the closed system without valves, and this loss is inherent for the case with intake and exhaust processes.

After 10 cycles of intake, expansion and exhaust processes as a warming-up operation, data for 5 cycles of intake, expansion and