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Timing optimization of single-stage single-acting reciprocating expansion engine based on exergy analysis

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ABSTRACT

For recovering the waste potential energy of natural gas during pressure reduction in City Gate Stations (CGS), Reciprocating Expansion Engine (REE) could be utilized instead of throttling valves. The main goal of this theoretical analysis is to optimize ports opening and closing time of REEs. The first and second law analysis of the natural gas inside the cylinder, as a control volume, has been carried out for optimization. The optimization is based on Genetic Algorithm from exergy efficiency concept. The influence of the REE pressure ratio on the exergy efficiency is analyzed by numerical calculations too. In general, the results of the analysis showed that exergy efficiency based on optimization of inlet/outlet ports opening and closing timing has a huge impact on the REE performance. It was found that for optimized timing, exergy destruction due to outlet throttling is two or three times of destruction due to inlet throttling, in one case 14.5 kW against of 6 kW. It is also found that engine size does not have much impact on the port timings. The results showed that exergy destruction due to mixing and heat transfer can be neglected, although friction and inlet/outlet throttling have a significant impact on exergy loss. The portion of friction is about 5–10% in all cases. It is also found that inlet pressure has significant effects on optimized port timing. In cases of inlet pressure of 70 bars, inlet processes should be finished at 63° and in cases of 55 bars it is about 72°. If a REE is optimized for inlet pressure of 70 bar, it should not be utilized for inlet pressure less than 30 bar.

1. Introduction

Natural Gas (NG) pressure should be reduced in City Gate stations (CGS) before its transmission for being consumed in local distribution systems. The expansion valve is traditionally used for pressure reduction. Expansion valve destroy a lot of potential energy of high pressure natural gas during pressure reduction. There are a lot of researches to analyze the methods for recovering this huge wasted energy. These methods consist of using combined heat and power (CHP) and turbo expanders [1–6]. Exergy recovery and energy analysis of pressurized gas in natural gas expansion plants by using of internal combustion engine (ICE) and an organic Rankine cycle (ORC) has been studied [7–9].

A few studies have been carried out on using turbo expanders instead of throttling valve to recover the wasted potential energy in natural gas pressure reduction [10–12]. Using of solar heating unit due to decreasing fuel consumption and installing turbo expander instead of throttling valve for power generation has been studied [13].

It has been shown that the amount of pressure drop is the main parameter which has a huge impact on the amount of power output. The effect of turbine's isentropic efficiency on power output has been analyzed too [10]. It has shown that the variation of flow rate has a significant effect on the amount of power generation [11]. Another investigation shows that installing turbo expander in parallel with expansion valve has financial benefit over a year [12].

There is a very good possibility of recovering energy from pressurized gas during pressure reduction using REE. Power generation from REE is clean and could be considered as green energy. A schematic diagram of a REE is shown in Fig. 1. Nowadays, employing natural gas reciprocating single or double acting expansion engine in parallel with expansion valve is getting a popular alternative option [14]. Single-acting REE (see Fig. 2) which could be made less expensive than double acting only has one expansion stroke per revolution of crankshaft. Therefore, the expansion of gas will take place on the top side of the piston. This means that the piston is only powered by gas on its down stroke and needs the momentum of the crankshaft to force it back up from Bottom Dead Center (BDC) to Top Dead Center (TDC).

Although REEs have been employed in NG industries for pressure reduction, there is a very limited research about these

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Nomenclature

A	instantaneous heat transfer area (m^2)
$A_{s,d}$	inlet/outlet port area (m^2)
b	specific flow exergy function (kW)
C_L	clearance volume (m^3)
C_P	constant pressure specific heat (j/kg K)
C_V	constant volume specific heat (j/kg K)
D_i	piston diameter (m)
D_o	outside diameter (m)
E	energy (kW)
d	port diameter (m)
f	friction factor
h	specific enthalpy (j/kg)
$\dot{I}$	exergy destruction (kW)
L	connecting rod length (m)
t	time (s)
L_r	ring wide (m)
$\dot{m}$	mass flow rate (kg/s)
N	motor speed (rpm)
P	pressure (Pa)
$\dot{Q}$	heat transfer rate (kW)
R	crank radius (m)
R_g	constant coefficient of methane (j/kg K)
r_p	pressure ratio
$\dot{S}_{gen}$	entropy generation (W/K)
s	specific entropy (j/kg K)
T	temperature (K)
T_0	dead state temperature (K)
T_a	ambient temperature (K)
u	internal energy (j/kg)
U	overall heat transfer coefficient (w/m^2 K)
V	volume (m^3)
W	power (kW)
x	piston displacement (m)
γ	isentropic power
Ψ	exergy efficiency
θ	instant angle of connecting rod (°)
$\dot{\Xi}$	rate of exergy transfer (kW)
ω	rotational speed (rad/s)

Subscripts

av	average
0	clearance volume
b	brake work
c	control volume of expansion engine
d	discharge
dis	cylinder volume
f	friction
i	identifier for inlet flow stream
id	ideal
ind	indicator
in	inside cylinder
mix	refer to mixing
out	outside cylinder
Q	refer to heat transfer
r	ring piston
s	suction
t	total exergy transfer
th	refer to throttling
w	wall cylinder

engines. One report shows that the amount of power generation by REE from natural gas potential energy depends on mass flow rate, pressure ratio and NG preheating [14]. Since experimental investigation of REE is very costly, computer modeling for analyzing and the engine alternative designing is more affordable. Farzaneh-Gord and Jannatabadi [15] modeled the single-acting REE and analyzed the effect of various parameters such as speed, port and piston diameter, connecting rod length and crank radius on the engine performance and proposed the optimized amount of these parameters. Farzaneh-Gord et al. [16] studied utilizing a REE at much lower pressure (between 4 and 17 bar) for Town Border pressure reduction Stations (TBS). In their study AGA8 equation of state has been used for calculating natural gas thermodynamic properties.

From the point of geometric and simulation view, a REE is similar to a reciprocating compressor. It just acts the reverse of compressor but instead of valves, spool valves are used for controlling inlet and outlet mass flow. Therefore, similar research on reciprocating compressors is worth reviewing. A lot of researches

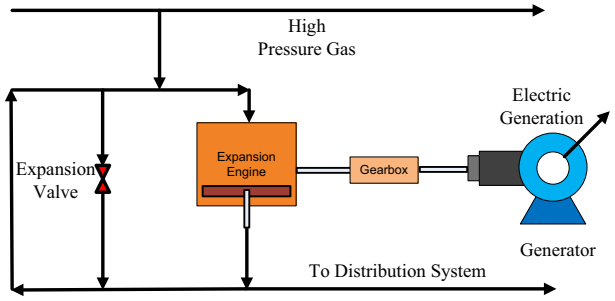

Fig. 1. A schematic diagram of installing an expansion engine in a CGS.

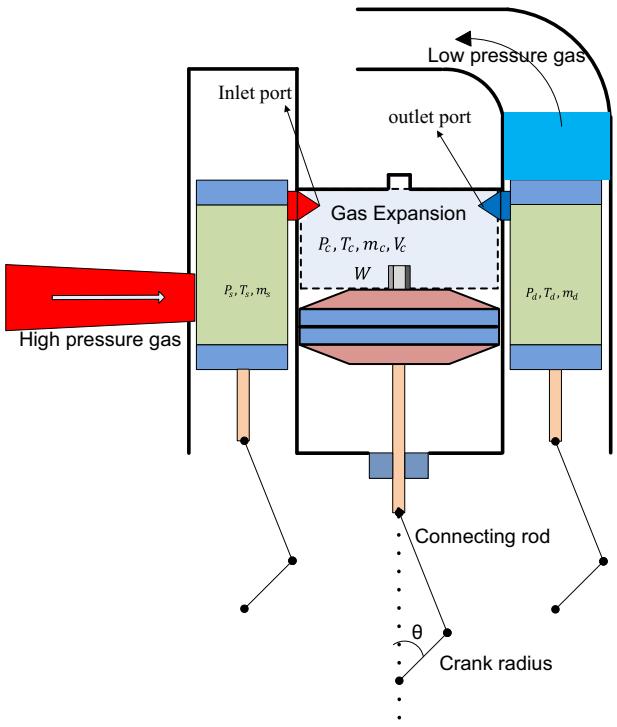

Fig. 2. A schematic diagram of a single acting reciprocating expansion engine.

have been reported on the further development of the methods of physical simulation and thermodynamic processes occurring on the reciprocating compressors to predict overall performance