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A novel expander-depending natural gas pressure regulation configuration: Performance analysis

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HIGHLIGHTS

- A novel system which can recover pressure energy as well as regulate pressure is proposed.
- Round trip efficiency of the whole system (including gas source) reaches up to 25%.
- Isentropic efficiency of expander has great influence on round trip efficiency.
- Wide installation of the system bring about rich economic and environmental benefit.

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ABSTRACT

Natural gas (NG) is delivered with abundant pressure energy from the gas station to various industrial users and residents. The commonly used Throttle Valve Pressure Regulation configuration can achieve stable downstream pressure, but the gas pressure loss is great. Additional turbines could be employed to recover the pressure energy, but hard to present a high efficiency. This work innovatively proposes an Expander-Depending Natural Gas Pressure Regulation configuration, which can regulate the NG pressure and harvest the pressure energy as well. A single screw expander is used to recover the pressure energy, whereby an air-source heat pump acts as a heat source to warm the cold gas. A thermodynamic model is established to evaluate the energy and exergy performance. Thermodynamic analyses show that the daily round-trip efficiency of the system, including both the NG source sector and the expander-depending NG pressure regulation sectors, can be more than 25% while the daily exergy efficiency and the daily power output of the expander-depending gas pressure regulation sector come up to 37.02% and 60.9 kWh respectively under the inlet NG pressure of 0.6 MPa and the outlet NG pressure of 0.1 MPa, and the volume flow rate from 30 Nm^3/h to 350 Nm^3/h. The round-trip efficiency, the exergy efficiency and the net power output dramatically increase with the isentropic efficiency improvement of the single screw expander. The proposed expander-depending natural gas pressure regulation unit can produce rich economic and environmental benefits and promise a bright future in the engineering application.

1. Introduction

The efficient use of off-peak electricity, excess solar radiation, excess wind energy, as well as other non-dispatchable renewable energy have been paid much attention recently to combat the climate change and environmental problems. Energy storage is a key technology to store the off-peak energy and release it in case of need, which can efficiently increase the utilization ratio of the aforementioned excess energy. The compressed air energy storage has been widely studied during the last decade [1,2]. In the discharge cycle of a compressed air energy storage system, the air turbine works in a steady state, where the air volume flow rate, the rotational speed and the power output of the turbine are all generally kept constant [3,4]. The compressed air, as the only energy carrier, expands to the ambient air and outputs work directly [5,6].

As an efficient and clean fuel, NG has been widely used around the world either in industrial or civil sectors [7,8]. Besides the inherent chemical energy, the natural gas can also reserve electricity by increased pressure, liquified NG [9] and NG hydrate [10].

It is noticeable that the peak consumption of both electric power and NG appears almost at the same time period during a day. Therefore, the NG energy storage shows big advantages over the compressed air energy storage in the case: at off-peak hours (usually at night time), the excess and much cheaper electricity is stored in form of high pressure

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Nomenclature

Variables

$\dot{A}n$	exergy destruction, kW
ex	specific exergy, kJ/kg
$\dot{E}$	energy flow, kW
$\dot{E}x$	exergy flow, kW
h	specific enthalpy, kJ/kg
m	mass flow, kg/s
P	power, kW
$\dot{Q}$	heat flow, kW
s	specific entropy, kJ/kg
t	celsius temperature, °C
T	kelvin temperature, K
V	NG volume flow rate, Nm^3/h

Abbreviations

NGPR	natural gas pressure regulation
ED-NGPR	expander-depending natural gas pressure regulation
EG	excitation generator
FVC	frequency-variable compressor
HPNG	high pressure natural gas
LPNG	low pressure natural gas
NGC	natural gas compressor
NG	natural gas
PS	pressure sensor
RTE	round-trip efficiency
SC	system controller
SSE	single screw expander
TTV-NGPR	turbine-throttle valve natural gas pressure regulation
TV-NGPR	throttle valve natural gas pressure regulation

Greek

η	efficiency, dimensionless
φ	exergy efficiency, dimensionless
ϕ	exergy index, dimensionless

Subscripts

airto	air to evaporator
airfrom	air from evaporator
coef	coefficient
con	condenser
da	daily
e	electrical
eva	evaporator
EG*p*	net power output
fan	evaporator fan
i	number, 1, 2, 3, 4, 5, a, b, c, d
in	inlet of a device
loss	heat loss
m	mechanical
M	motor
out	outlet of a device
peak	peak value

NG, while the by-produced heat of compression is utilized for building heating, hot water, etc.; at peak hours (usually at day time), high pressure NG is released and expands to generate electricity while the released NG is supplied to the end-users and the cold of expansion could be output to the buildings, the low temperature warehouse, and so on. The NG compressing and releasing processes require high stability in pressure and high fluctuation in volume flow rate. However, the present throttle valve NG pressure regulation (TV-NGPR) configuration can regulate the gas pressure but fails to recover the pressure energy [11].

Currently, the NG pressure energy recovery has been attracting more and more attention due to the call for energy saving and greenhouse gas reduction. Most of the researches focus on the turbine, the preheating/heating source, the power production, the utilization of cold energy, the thermodynamic analysis, the thermos-economic assessment, the process optimization and the utilization of renewable energy [12–23].

Yang et al. [12] considered the pressure energy recovery of the supersonic separating process for NG dehydration and developed a CFD model to evaluate the NG dynamic performance at various Mach numbers. Their numerical results were verified with the experimental results at a maximum error of around 8.69%. He and Ju [13] proposed the utilization of NG pressure energy to liquefy NG and achieved a NG liquefication rate of 10–15%, while the energy consumption for the liquefication process can be decreased to 0.03975 kWh/Nm^3. Neseli et al. [14] considered a turbine-throttle valve natural gas pressure regulation (TTV-NGPR) configuration, in which a turbine was installed parallelly to the TV-NGPR. In this configuration, the turbine was employed to generate electricity while the throttle valve regulating downstream pressure and the gas burners preheating the NG prior to the turbine and the throttle valve. However, the throttle valve and the daily variation of the NG volume flow rate were not considered in their studies. Sanaye et al. [15] integrated a gas engine into the TTV-NGPR to preheat NG and generate electricity.

To decrease the fossil fuel consumption and reduce the CO_2 emission, the solar energy was used for the NG preheating, and the thermo-economic analyses were conducted by case studies [16,17]. Farzaneh-Gord et al. analysed the feasibility of the solar energy collectors integrated with the TTV-NGPR. Then, a new configuration [18] was put forward, and the energy and exergy performance were evaluated [19]. Due to the instability of solar radiation, it was proposed to pump the underground hot water to preheat the NG, and the thermo-economic analysis was conducted on the combination of the geothermal energy and the TTV-NGPR to give an internal return ratio of 0.155 [20].

In addition, the fuel cell [21] and ground-coupled heat pump with vertical ground heat exchanger [22–24], the vortex tube, the bio-fuel [25], the internal engine and the Organic Rankine Cycle (ORC) [26] were integrated respectively with the TTV-NGPR, and the energy and exergy performance, the thermo-economics and the CO_2 emission were evaluated. Moreover, to increase the system performance, a double-stage turbine and CHP (Combined heat and Power) were integrated to the TTV-NGPR with the performance ratio of 0.895 and exergy efficiency of 49.2% [27].

The single screw expander (SSE) is one of the compact positive-displacement expanders and has been focused on in recent years [28,29]. It usually works as the engine in the Organic Rankine Cycle to harvest the electricity from the low-temperature heat sources in industry [30–32]. These indicate that the single screw expander can meet the need for recovering low-grade heat and exhibits better application prospect in the field of thermal energy engineering. To know the operating performance, Lu et al. [33] conducted experimental study on the single screw expander with compressed air as working fluid and achieved an isentropic efficiency of 65% and temperature drop of 70 °C. Wang et al. [34] found the power output of the single screw expander was approximately proportional to the rotational speed within the range of rated speed. The most recent researches proved the feasibility of the single screw expander in the practical application [35].