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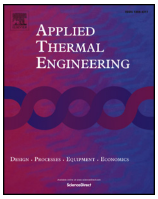

Research Paper

Theoretical analysis for heat exchange performance of transcritical nitrogen evaporator used for liquid air energy storage

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HIGHLIGHTS

- Heat exchange performance of transcritical N_2 with a pair of hot fluids is analyzed.
- Local performances are highly dependent on local heat capacity rate ratio.
- Exergy efficiency and entransy dissipation have similar performance behavior.
- N_2 pressure increase elevates overall performance but lessens captured cold amount.
- Optimal ratio of heat load or conductance distribution between hot fluids is obtained.

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Heat exchanger
Supercritical nitrogen
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Exergy efficiency
Energy storage

ABSTRACT

In view of violent changes of thermo-physical properties, the segmental design method is adopted to explore the heat exchange performances of the transcritical nitrogen (T-N_2) evaporator used for liquid air energy storage, in which cold N_2 is heated up successively by hot propane and methanol in two wide temperature sections. The local heat capacity rate ratio between cold and hot fluids has crucial effects on the local heat exchange performance of evaporator, such as local effectiveness, local entransy dissipation, and local required heat conductance or local heat transfer rate. They have extremums near the positions where the local heat capacity rate ratio equals one, but their optimal values need to be determined by combining the changing trend of the local heat capacity rate ratio. The total heat exchange performance of evaporator is evaluated using total entransy dissipation and total exergy efficiency. When the heat load is fixed, the total performance is improved with the decrease in the mass flow rate of methanol, but at the expense of the required total heat conductance; The total performance can be optimized by precisely tailoring the heat load ratios between the two temperature sections. When the heat conductance is given, the optimum total performance can be obtained by adjusting the mass flow rate of hot fluids at a fixed heat conductance ratio; Increasing the heat conductance ratio of the low temperature section can further elevate the optimum total performance whereas the affordable heat load or the outlet temperature of N_2 is notably decreased. Increasing N_2 pressure elevates the total performance of evaporator but diminishes the extractable cold amount from the liquid N_2 in the same temperature rise. This work is beneficial for selection of key parameters to achieve optimal operation of the T-N_2 evaporator.

1. Introduction

Liquid air energy storage (LAES) as a promising solution for grid scale energy storage has attracted much attention in recent years [1–5]. The LAES uses liquid air/nitrogen (N_2) as both storage medium and working fluid for charging and discharging processes of electrical energy. During the charging process, excess or cheapest electricity drives air liquefaction and separation plants to produce liquid N_2 stored in cryogenic tanks at the nearly atmospheric pressure. During the discharging process, the liquid N_2 is first pressurized by a cryogenic pump and then heated up to expand in turbines to generate electricity. Cold thermal energy released in preheating of liquid N_2 during the discharging process can be captured to lessen refrigeration load of air liquefaction during the charging process. In view of time mismatch of the

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Nomenclature

Roman letters

c_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
D_{re}	relative difference
$\dot{E}_{dis}$	entransy dissipation ($W \cdot K$)
EX	flow exergy (W)
h	specific enthalpy ($J \cdot kg^{-1}$)
HA	heat conductance ($W \cdot K^{-1}$)
m	mass flow rate ($kg \cdot s^{-1}$)
mc_p	heat capacity flow rate ($W \cdot K^{-1}$)
M	number of sub-heat exchangers in the low temperature section
N	number of all sub-heat exchangers
Ntu	number of heat transfer units
P	pressure (Pa)
q	local heat transfer rate (W)
Q_{tot}	total heat load (W)
R_c	the ratio between the smaller and bigger heat capacity flow rates
$R_{c,hc}$	the ratio of heat capacity rate of hot fluid to that of cold fluid
s	specific entropy ($J \cdot kg^{-1} \cdot K^{-1}$)
T	temperature (K)

Greek letters

ε	effectiveness
η_{EX}	exergy efficiency
τ	the ratio of heat load in the low temperature section to that in the whole evaporator
φ	the ratio of heat conductance in the low temperature section to that in the whole evaporator

Subscripts

0	environmental conditions
c	cold fluid
h	hot fluid
hl	hot fluid in the low temperature section
hh	hot fluid in the high temperature section
i	inlet
j	local position
m	mean value
o	outlet

charging and discharging processes, the captured cold thermal energy required to be stored. Such a design of cold recycle based on cold storage in LAES significantly improves the overall system efficiency [2]. Conventionally, cold storage is implemented using packed beds of pebbles or rocks operating at nearly atmospheric pressure [6–8]. Operating experience of a 350 kW/2.5 MWh pilot plant located at the University of Birmingham manifested that the temporary cold storage using packed beds results in round trip efficiency improvement of LAES by ~50%. However, the dynamic effects in packed beds caused by thermal front propagation can lead to an undesired increase by 25% in the energy consumption of air liquefaction [9]. Therefore, it is required to design a novel high-efficiency cold storage unit.

Similar to sensible heat storage using liquids as medium, Li et al. [10] proposed a cold storage unit based on combination of two thermal fluids, which were used as both heat transfer fluids and cold storage mediums. Both She et al. [11] and Pen et al. [12] also adopted the same cold storage unit in their proposed novel LAES system. The reason for adopting two thermal fluids is that no single fluid can work totally in the form of its liquid state in the wide working temperature range of the liquid N_2 preheating process. The two fluids are propane and methanol selected owing to their suitable working temperate ranges and comparatively large heat capacity [10]. A two-tank configuration was designed for each of the two fluids to recover and store cold energy, which can realize quasi-steady heat transfer in heat exchangers to overcome dynamic effects in packed beds [13]. The proposed unit can notably simplify the LAES system involving cold storage and offer more straightforward and flexible operating strategy with respect to the conventional packed beds [10]. The calculations indicated that the selected thermal fluids exhibit higher volume-based energy storage density than pebbles or concrete [10,14]. This implies that a more compact system can be obtained by using the selected fluids as cold storage mediums.

The discharging pressure, namely the inlet pressure of the first stage turbine, is one of major operating parameters influencing the performance of LAES system. With the increase in the discharging pressure, the resulting specific expansion work increases while the recyclable cold amount diminishes [9]. In order to increase the output power of turbines, the liquid N_2 is generally pressurized above the critical pressure of N_2 before the inlet of first stage turbine [9,13]. Thus N_2 will undergo phase transition from the liquid state to the supercritical state in the liquid N_2 preheating process. For convenience, this phase transition is also called evaporation similar to liquid–gas phase transition, and the corresponding heat exchanger is named transcritical N_2 (T-N_2) evaporator in the present paper. The performance of the evaporator determines the amount of recovered cold and the inlet temperature of turbines in a LAES system, and thus has crucial influences on the operation efficiency and stability of the system [9]. However, the thermodynamic properties of N_2 change dramatically around the pseudo-critical temperature, which makes the heat transfer in the evaporator rather complicated and the design of the evaporator very challenging.

Some studies have been devoted to the heat transfer characteristics of supercritical N_2 [15–19]. Dimitrov et al. [15] conducted experiments on forced convective heat transfer of supercritical nitrogen at a pressure of 4 MPa in a vertical tube. The results indicated that the heat transfer can be enhanced when the difference between wall and bulk temperatures spans the drastic variation region of the thermo-physical properties of N_2. Zhang et al. [17] carried out experimental and numerical studies on flow and heat transfer of supercritical N_2 in a vertical mini-tube. They reported that there is considerable discrepancy in Nusselt numbers between the experimental results and the predictions by the existing correlations. Ciprian et al. [19] numerically examined the heat transfer coefficient of supercritical N_2 in the large specific heat region flowing upward in a vertical tube under different operating pressures. They found that the increase of heat flux could cause heat transfer deterioration. The above studies almost focus on the heat transfer behaviours of supercritical N_2 under fixed heat flux conditions. Actually, the heat transfer in the evaporator is coupled between the N_2 and the transfer fluids, and hence the heat transfer condition of N_2 is changing along the flow direction of N_2. Therefore, deep understanding of coupled the heat transfer behaviours between N_2 and two heat transfer fluids in the evaporator is crucial to the optimization design of evaporator for improving performances of the LAES system.

From the above, although such a T-N_2 evaporator including the combination of propane and methanol as heat transfer fluids has been adopted by several researches [10–12], studies available in the literature have not addressed the following key aspects: (1) the local and overall heat exchange performances of the evaporator coupled with three fluids in the case of drastic change of the thermo-physical properties of N_2; (2) how to select the key operating parameters, including mass flow rates of heat transfer fluids, inlet pressure of N_2, and heat