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Exergy analysis of LBE-helium heat exchanger in the experimental cooling loop based on accelerator driven sub-critical power system

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ABSTRACT

The intermediate heat exchanger (IHX) is one of the most important equipments of accelerator driven sub-critical power system (ADS) in which the heat transfers from high-temperature lead bismuth eutectic (LBE) to the low-temperature helium gas. The efficiency improvement and optimization of heat exchanger could improve the work capability of the power system. In present work, the LBE-helium two-loop cooling system based on ADS and a specialized experimental platform of IHX are introduced. The effects of inlet conditions on the exergy efficiency of an LBE-helium heat exchanger are investigated at the LBE temperature of 300–490 °C and the LBE flowrate of 1–200 kg/s. The unavoidable exergy loss of IHX is investigated using the method of advanced exergy analysis. The results indicate that the minimum of exergy efficiency of LBE-helium heat exchanger is presented when the LBE mass flowrate increases gradually. The decreasing inlet flowrate of helium gas is helpful to improve the exergy efficiency. When exergy losses of LBE and helium gas are the minimum value, the minimum value of exergy loss of IHX is obtained, and that is the unavoidable exergy loss. At conditions of the fixed total heat transfer and area of heat transfer, the optimal ratio of unavoidable exergy loss caused by temperature difference and caused by pressure drop is obtained for the minimum exergy loss. These are practically helpful to improve thermodynamic process of IHX focused on the reducing avoidable exergy loss.

1. Introduction

As general equipments, heat exchangers are used widely in energy, power, petroleum, chemical and other industries. In nuclear power system, the large amounts of heat generated by nuclear reaction are transferred to the coolant or the working medium in the heat exchanger. The efficiency of heat exchanger determines the work capability of the power system. Thus efficiency improvement and the optimization of heat exchanger continue to be an important issue in the energy usage. Since the amount of heat loss is generally small, the efficiency of heat exchanger is usually high, and the energy loss of heat exchanger is also small generally. However, the temperature difference must be existed for heat transfer in heat exchangers. The flow resistance is also inevitable in the process of heat transfer. Thus the energy loss, namely exergy loss caused by temperature difference and friction resistance is also inevitable.

The concept of exergy is based on the second law of thermodynamics and is defined as the maximum theoretical work obtainable of a system [1]. Exergy analysis can be generally applied to energy systems. This analysis method appears to be a more powerful tool than energy analysis for power cycles because it can be used to determine the true magnitudes of losses and their causes and locations, and improve the overall system and its components [2]. The major part of this analysis method includes determining exergy efficiencies for an overall system or the individual components making up the system. Exergy efficiency is one of the most frequently used parameters in thermodynamics investigation because it can denote how about the quality of the energy conversion. Because of being used usually without proper definition, the exergy efficiency is also one of the most frequently misused parameters. Therefore, it should be used to analyze the system or component carefully.

Conventional exergy analysis can quantitatively determine the efficiency of thermodynamic process. However, this method cannot identify the share of inefficiency that can be avoided [3], and cannot assess the improvement potential [4,5]. Advanced exergy analysis is relatively new to energy system engineering. Advanced exergy analysis involves splitting the exergy destruction of the system components into two parts of avoidable and unavoidable [6]. The unavoidable exergy loss is defined as the technically or economically unavoidable minimum exergy loss. This will give engineers a better understanding about the exergy destruction from a

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Nomenclature

A	heat transfer surface area, m^2
c_p	specific heat at constant pressure, J/(kg·K)
Ex	exergy, W
h	heat transfer coefficient surface, $W/(m^2 \cdot K)$
k	heat transfer coefficient of heat exchanger, $W/(m^2 \cdot K)$
m	mass flowrate, kg/s
P	pressure, Pa
Q	heat transfer rate, W
R_g	the gas constant of helium gas, J/(kg·K)
S_{gen}	entropy generation rate, W/K
T	temperature, K
Greek symbols	
η_{ex}	efficiency
ρ	density, kg/m^3
Δ	difference
Superscripts	
min	minimum
max	maximum
UN	unavoidable
Subscripts	
0	surrounding
1	inlet
2	outlet
He	helium gas
L	loss
LBE	lead bismuth eutectic
ΔT	due to heat transfer
ΔP	due to friction

single component caused by its own inefficiency, or by the remaining inefficient components in the system and the interactions among system components. Advanced exergy analysis has been applied previously to analyze many equipments and systems, such as a fluidized bed coal combustor and a heat recovery steam generator [7], a complex steam boiler plant [8], a combined cycle power plant [9], a trigeneration system [10], an ejector refrigeration system [11], a low temperature enhanced geothermal system [12], an absorption cooling machine [13], an air conditioning system incorporating thermal energy storage [14], the process of regasification of LNG [15], an aircraft gas turbine engine [16]. Yang et al. [6] evaluate the performance of a Fushun-type oil shale retorting process using the advanced exergy analysis method. The results indicate that 80.46% of the total exergy destruction is endogenous. About 45.40% of the exergy destruction is unavoidable and cannot be reduced due to technical limitations. Kelly et al. [17] discussed four different approaches for calculating the endogenous part of the exergy destruction. In the paper, the authors presented the advantages, disadvantages and restrictions for applications associated with each approach and concluded that only structural theory did not give reasonable results. Morosuk and Tsatsaronis [18] applied this concept to vapor-compression refrigeration machines using different refrigeration fluids. The paper aims to demonstrate the effect of different refrigerant properties on the results of advanced exergy analysis. Morosuk and Tsatsaronis [19] deal with an application of an integrated conventional and advanced exergy analysis to a supercritical CO_2 power cycle operating in hot climatic conditions. The objective is to obtain detailed useful information about the optimization of the structure and parameters of the system being considered. Conventional exergy analyses have some limitations, which are significantly reduced by the so-called advanced analyses.

Based on the advanced exergy analysis, the improvement of thermodynamic process focuses on the reducing avoidable exergy loss instead of the general exergy loss. That will achieve the real purpose effectively. In this present paper, the LBE-helium heat exchanger, which is the key equipment of the two-loop cooling system in ADS, is investigated used the method of advanced exergy analysis. Effects of inlet conditions on the exergy efficiency of LBE-helium heat exchanger are analyzed. The minimum exergy loss of LBE and helium gas is obtained to determine unavoidable exergy loss. These results are useful to improve the exergy efficiency of the LBE-helium two-loop cooling system. These will also help to improve the efficiency of the whole ADS.

2. Two-loop cooling system based on ADS

2.1. ADS and LBE-helium two-loop cooling system

From nineties of last century, ADS has been used to proliferate and transmute spent nuclear materials. ADS takes the spallation neutrons as the external neutron source to drive the sub-critical blanket system. ADS can not only significantly reduce the radiation lifetime, level and volume, but also output extra energy so as to improve the utilization of fuel. These advantages result in ADS becoming the preferred technology approach to effectively dispose the spent nuclear material [20]. In a comparative study, entitled "Accelerator-Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles", the Nuclear Energy Agency (NEA) of Economic Co-operation and Development (OECD) [21] drew a conclusion that, "ADS has the advantage that it can burn pure minor actinides while avoiding a deterioration of the core safety characteristics". ADS have been universally regarded as the most promising approach to dispose the long-lived nuclear wastes.

The program of Future Advanced Nuclear Fission Energy is carried out by Chinese Academic Society to explore the application technology of ADS. For this project, LBE is the suitable coolant and spallation target material due to its favorable properties such as chemical inert and heat transfer performance. Moreover, the cool system of ADS can be operated at the lower conditions of temperature and pressure resulting from the suitable thermophysical properties of LBE, such as the lower melting point and the higher boiling point. As a new technical explore of nuclear energy, helium is used for the coolant and working gas in two-loops cooling system [22]. Helium is the inactive gas. Its performance also is excellence. In addition, helium has a good advantage in the turbomachinery [23]. Fig. 1 shows the schematic of LBE-helium two-loop cooling system based on ADS.

A regenerative Brayton cycle based on ADS power system is illustrated in Fig. 1. LBE is the coolant of primary loop which flows through the reactor core and takes away the heat of nuclear reaction for keeping the stable and safe temperature. The high-temperature LBE coming from the reactor enters the IHX with temperature of $T_{1,\mathrm{LBE}}$, the cooled LBE with temperature of $T_{2,\mathrm{LBE}}$ returns into the reactor. The secondary loop is an irreversible Brayton cycle system. The helium gas, which is heated to temperature of $T_{2,\mathrm{He}}$, by high-temperature LBE in the IHX, enters the turbine to do work; the helium gas coming from the turbine is precooled in the regenerator and further cooled in the condenser. The cooled helium gas