Energy Saving Opportunities in an Air Separation Process

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ABSTRACT

The process of a large-scale air separation unit is simulated based on the industrial process and operational parameter of a petrochemical company by using ASPEN PLUS. The actual operating performance is analyzed for the total site. According to the simulation results, exergy efficiency of major equipment is analyzed. The optimization problem can be solved by a new algorithm, which combines genetic algorithm with linear programming. Accordingly a modified air separation process is proposed. The equipment deficiency is overcome in the new process. Also the nitrogen expansion and the structure packing column are added. Meanwhile the pinch analysis is done for the new process. The results of the pinch analysis considering the impact of phase transition agree better with industrial data than those without doing so. The energy consumption can be 7.55MW lower than the original process. The total energy efficiency can be raised by 27.21%. Finally seven unified principles for energy saving, which can be widely used in air separation process, are summarized.

1. INTRODUCTION

Increased attention has been focused on the energy-saving technology since the energy crisis. The essence of energy-saving is to utilize energy efficiently. Accordingly more production and work can be provided. For the energy intensive air separation process, exergy analysis and energy integration are useful tools. Meanwhile the technology of CO_2 emission reduction has been studied widely (Yu *et al*., 2010). By energy integration both power utilization and fuel combustion can be reduced in the air separation process. Therefore the energy efficiency can be improved with CO_2 emission control (Linnhoff and Dhole, 1992).

In the 1980s, the presentation of pinch technology was a great breakthrough. This technology had become a conventional method of chemical engineering system design and modification (Robin, 1992). In the 1990s, a new concept Total site integration (TSI) was proposed, which included the combined integration of procedures and utilities (Dhole and Linnhoff, 1993). Meanwhile the total site integration with multi-process multi-objective was introduced (Grossmann and Westerberg, 2000). Then, mixed integer nonlinear programming (MINLP) and artificial intelligence (AI) algorithms were brought into this area. Also the region and methods of energy integration were expanded (Bagajewicz and Rodera, 2002). It was pointed out that the heating load could be divided into different pressure levels. In addition cooling load could utilize the cooling water and a part of low pressure steam. Because the steam pipe networks had been fixed in this project, the method of top-level analysis was used. Thereby integration was started directly from the utilities while constant pressure levels were maintained (Makwana *et al.*, 1998). According to the superstructure method, this problem could be described as a MINLP model (Kokossis and Floudas, 1991). But this kind of mathematical model was difficult to solve. It was often caught in the NP-hard problem to solve such models (Grossmann and Westerberg, 2000). ASPEN and MATLAB software packages were linked as calculation tools in this paper. The multi-objective genetic algorithm (GA) was used to solve the superstructure model. Finally the results obtained agreed well with the experiment data.

Based on the TSI ideas above, energy-saving opportunities are discussed. The air separation system is simulated based on the industrial data by using ASPEN PLUS. According to the simulation results, the actual operating performance and exergy efficiency of major equipment are analyzed. The major problems of this process are discovered. Then an improved air separation process is proposed with procedures and utilities coupled. The exergy and pinch analysis are done for the new process. It is shown that the energy consumption can be 7.55MW lower than the original process through the technical retrofit and the energy efficiency can be raised by 27.21%. Based on energy integration technology, seven unified principles are summarized for energy-saving.

2. Theory Summary

2.1 Original Air Separation Process

Cryogenic air separation unit (ASU) is a process of high energy consumption. The energy-saving opportunity of ASU has been studied for long. The exergy efficiency and structure packing method are analyzed (Yong *et al.*, 2002). And the heat integration method is reviewed (Smith and Klosek, 2001). But the total site optimization combined with utilities has not been considered in the studies above. The referred ASU is located in a chemical plant in northwest China, which produces nitrogen (99.999% purity) and oxygen (98% purity) for synthesis of ammonia. The ASU process is shown in Fig.1. The feed air is compressed by the air compressor K1 to 6.45 bar. Then it is sent into the molecular sieve to remove impurities such as water and CO_2. After it is cooled down to −171℃ by the main heat exchanger E1, the feed air is sent into the lower distillation column C1-C1. The overhead is pure nitrogen, and the bottom product is oxygen-enriched air liquid in which the oxygen purity is about 38%. 60% of pure nitrogen is fed into high-pressure nitrogen cycle, 40% is sent out as nitrogen product. Meanwhile a part of process gas, which is extracted from C1-C1 column, is sent into the expansion turbine T1. The oxygen-enriched liquid air and liquid nitrogen fraction from the C1-C1 column, through heat exchanger E2, flow into the upper distillation column C1-C2. The overhead of C1-C2 column is waste nitrogen, and the bottom product is liquid oxygen which is fed into the high-pressure oxygen cycle.

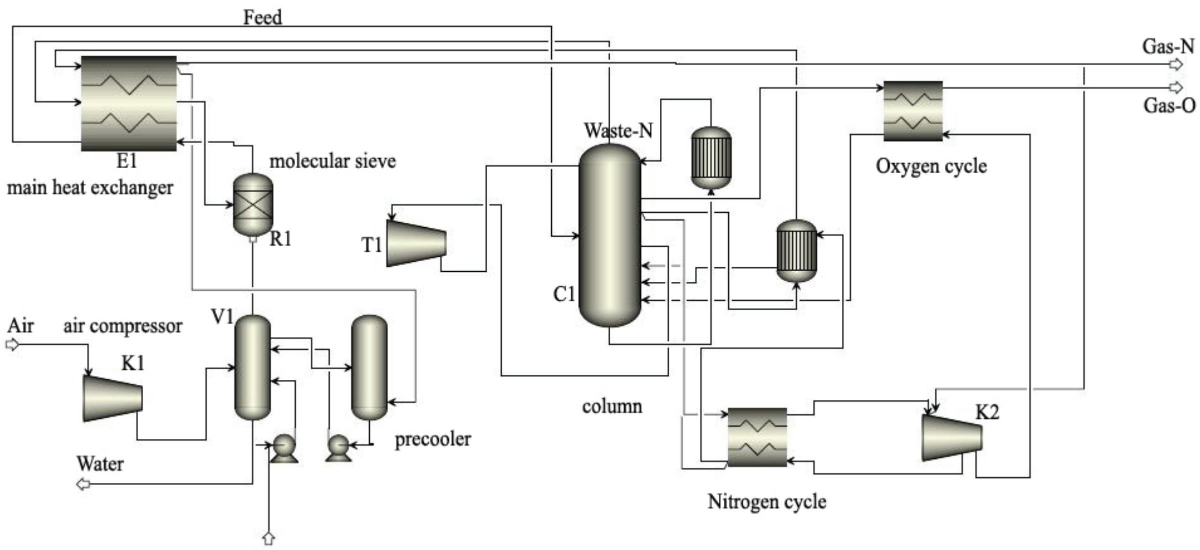

Figure 1. Original air separation process

2.2 Optimization Algorithm

Usually there are a series of solutions in multi-objective optimization. The solution can not be compared with each other, which is called non-inferior solution or Pareto optimal solution. It is impossible to improve one objective function while other objective functions are not affected. GA is a powerful tool to deal with the Pareto optimal solutions, because GA is designed for the population type operation which is focused on the group of individuals (Dietz *et al*., 2006). Thereby the multi-objective optimization problem can be expressed as follows.

$$Min\ F(x) = [f_1(x), f_2(x) \ldots\ldots\cdots, f_k(x)] \quad (1)$$

$$s.t.\quad g_i(x) \leq 0 \quad (2)$$

The comprehensive study of energy integration has been active for long. There have already been some mature theories and methods. Based on the superstructure and MINLP, comprehensive strategies have been widely studied. But such studies are often caught in the NP-hard problem, because there are too many compound modes. According to the current technology available, mature and reliable optimization method is still very rare. Multi-objective GA and MINLP are combined to solve the superstructure in this paper. The solutions obtained from the GA algorithm are delivered into the sub-problem. Then it can be solved by using linear programming (LP). Finally whether the constraints are satisfied should be checked. Only the optimal solutions which meet all the constraints can be preserved. By using the method above, it becomes easier to calculate the optimization problem and partition the program in the multi-objective and multi-constraint case. Detailed algorithm steps are as follows. 1) Construct the objective functions and code the variables; 2) Construct the process; 3) Process simulation and analysis; 4) Compare the performance of new process with criteria; 5) Remove the individuals which does not meet the criteria and carry on the crossover and mutation operation to obtain the new generation group; 6) If the maximum evolution generation is exceeded, go to the seventh step, on the contrary, turn to the first step; 7) Deliver the Pareto-optimal set into the sub-problem; 8) Solve the LP problem and check whether the constraints are satisfied;

2.3 Software Operating Environment

The ASU process is simulated by using ASPENPLUS. The units and entire process can be calculated with rigorous and precise algorithms. Meanwhile the optimizing and heuristic algorithm is programmed in the MATLAB environment. Therefore the computational capability of MATLAB and the process simulation capability of ASPENPLUS can be combined. Also the novel algorithms can be applied to the field of energy integration more easily. By calling certain MATLAB toolboxes, researchers can put more time into the pioneering work such as algorithm improvement and process optimization.

3. PROCESS SIMULATION AND INTEGRATION

3.1 ASU Process Simulation

The simulation results of ASU process are listed in Table 1 compared with the designed values. Under the actual condition the inlet air flow rate is only 89.2% of the designed value. That is because the air displacement of compressor K1 is lower than the normal value. N5 stands for the nitrogen product at 5 bar, while N80 is nitrogen at 80 bar. WN stands for the waste nitrogen gas.

Table 1. Original air separation process

Inlet flow				*Outlet flow*			
Stream	*DVF* Nm^3/h	*RVF* Nm^3/h	*PD* %	*Stream*	*DVF* Nm^3/h	*RVF* Nm^3/h	*PD* %
air	169291	151000	10.8	O_2	26901	24890	-7.5
				N5	6400	17826	178.5
				N80	29976	29779	-0.7
				WN	102131	76634	-25.0

To meet the increasing needs of synthesis ammonia, the amount of N5 is raised to 17826 Nm^3/h. Thus the total amount of nitrogen product rises up to about 48000 Nm^3/h. But the inlet flow rate is reduced as described above. Therefore, the burden of distillation column C1 is overwhelming. Meanwhile the amount and purity of oxygen product decreases slightly. The amount of WN is also decreased.

Energy consumption and generation of ASU are shown in Fig.2. It is indicated that the energy consumption of this plant mainly comes from steam and electricity. Steam is mainly used for the steam turbine. Electricity is for the water pumps, oil pumps and liquid oxygen pumps. Obviously in all sorts of power sources, HP and MP is the largest part of energy consumption. K1 and K2 compressors take up most of the energy, accounting for 86% of the total energy consumption. Thus the turbine efficiency directly affects the overall performance.

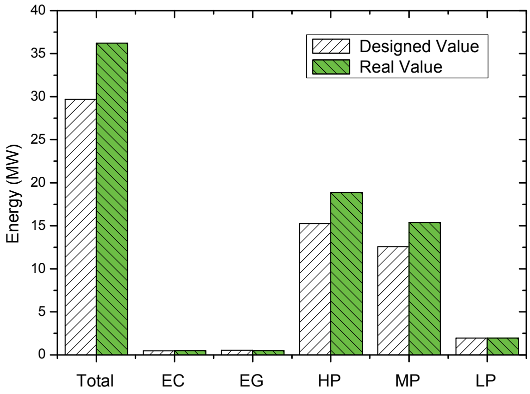

Figure 2. Energy utilities in air separation process

3.2 Exergy Analysis

Based on the second law of thermodynamics, the exergy loss is directly related to the efficiency of equipments. The more efficient units can be obtained by exergy analysis. In an actual process, various forms of energy are observed by the temperature, pressure and some other variables. Also by using the exergy method, the different forms of energy can be analyzed and evaluated to identify the optimal network. The total exergy can be expressed as the summation of physical exergy and chemical exergy.

$$Ex = E_{phys} + E_{chem} \tag{3}$$

Since the kinetic energy and potential energy are often ignored in a steady process, the physical exergy can be described as follows.

$$E_{phys} = (H - H_0) - T_0(S - S_0) \tag{4}$$

There is no chemical reaction in ASU process. Thus chemical exergy can be described as the form of diffusion exergy, which stands for the potential difference between the pure component and the standard component in the environment state. The exergy loss can be described as Equation (5). The exergy loss ratio can be defined as Equation (6).

$$E_{loss} = \sum_{in} Ex_i + \sum_{out} Ex_j \tag{5}$$

$$\eta = E_{loss} \Big/ \sum_{in} Ex_i \tag{6}$$

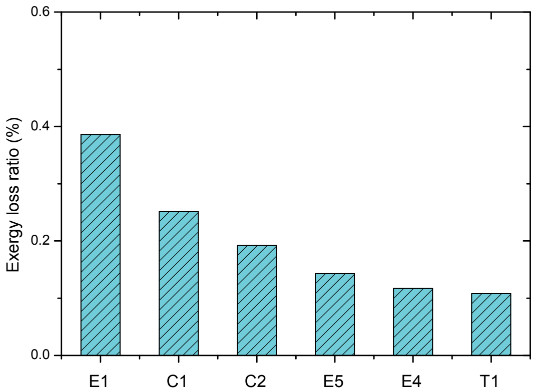

Figure 3. Exergy loss ratio of various equipments

In Fig.3, it is shown that most of the exergy is lost from the main heat exchanger E1. The technical reformation should be focused on the heat exchanger equipment. The efficiency of units needs to be improved. Furthermore, the process can be reformed locally to reduce the exergy loss. E5 and E4 stand for the high pressure cycles of oxygen and nitrogen. In such cycles, the expansion process can be applied instead of throttling process. Extra work will be produced by the expansion turbine. Meanwhile additional cooling capacity can be produced.

To design more efficient process, the superstructure of high pressure cycle should be constructed. The objective function can be described as exergy loss function and gas-liquid ratio function.

$$Min\ E_{loss} = \triangle E_{5-1} + \triangle E_{5-2} + \triangle E_{turbine} \tag{7}$$

$$Min\ Rx = G_{out} / L_{out} \tag{8}$$

In this problem the main variables include application of expansion turbine, outlet temperature of heat exchanger, split ratio and outlet pressure of expansion turbine. The application of expansion turbine is an integer variable. It can be assigned to 1 when turbine is applied. Otherwise it will be assigned to 0. The constraints include heat balance, mass balance, minimum temperature difference, non-negative constraint of heat transfer, rational range of temperature and reasonable range of split ratio. Consequently this problem has been summarized as a MINLP model. It can be solved by the algorithm combined multi-objective GA with LP. The mathematical method has been described in section 2.2.

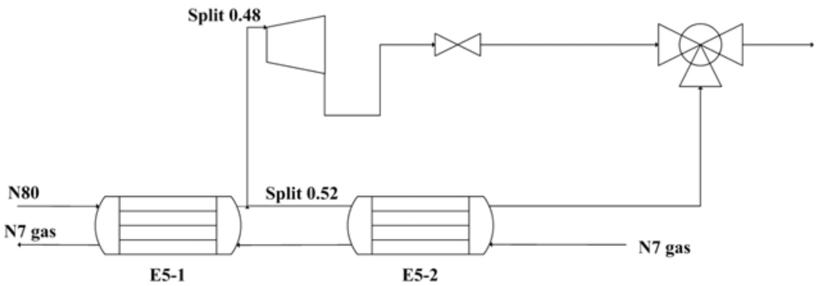

Figure 4. Improved high pressure expansion process

The result is shown in Fig.4. At the outlet side of N80, temperature is -170.5℃, the pressure is 9.3 bar, and the vapor fraction is 0.599. Respectively, the vapor fraction is 0.481 in the original process. Thus it is indicated that the cooling captivity is increased. And more liquid nitrogen is obtained, which will be fed into the top of column C1-C1. Therefore the status of distillation can be improved. In addition, 160kW shaft work can be made out by the turbine in the expansion process. Applying the same structure, the exergy efficiency of E4 process also can be improved. In E4 expansion process, the split ratio is 0.31 and 146kW extra work can be obtained.

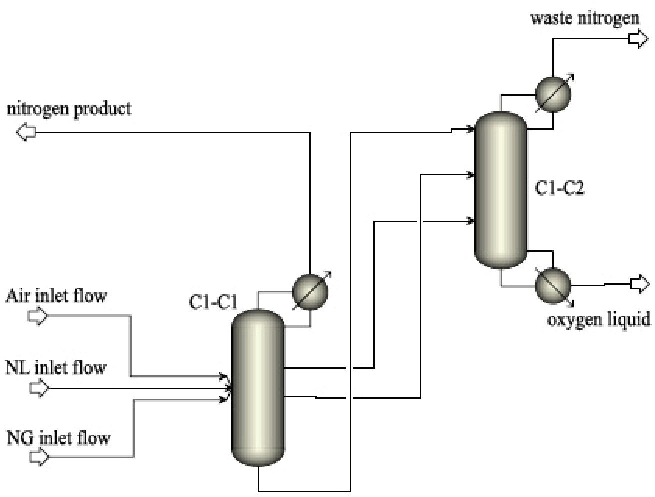

Figure 5. Optimization of double column distillation process

As shown in Fig.5, the process of double column distillation also can be optimized. The objective function can be expressed as exergy loss function and product flow rate function. Meanwhile the phase balance and rational range of mass transfer coefficient should be added into the constraints. The pressure drop between the top and bottom of the upper column C1-C2 is 1.2 bar. But the operating pressure is much lower than the column C1-C1. It is found that structure packing has better performance especially in the lower pressure of column C1-C2. That is because structure packing method can lead to higher separation efficiency and lower pressure drop. Respectively, in the medium pressure column C1-C1 a sieve tray or structure packing has the similar performance.

3.3 Pinch Calculation

In the cryogenic process, the exergy loss is much higher than that under the ordinary condition. Thereby the heat networks need to be matched efficiently. The pinch calculation has been done for the modified process. Fig.6 shows the heat network analysis.

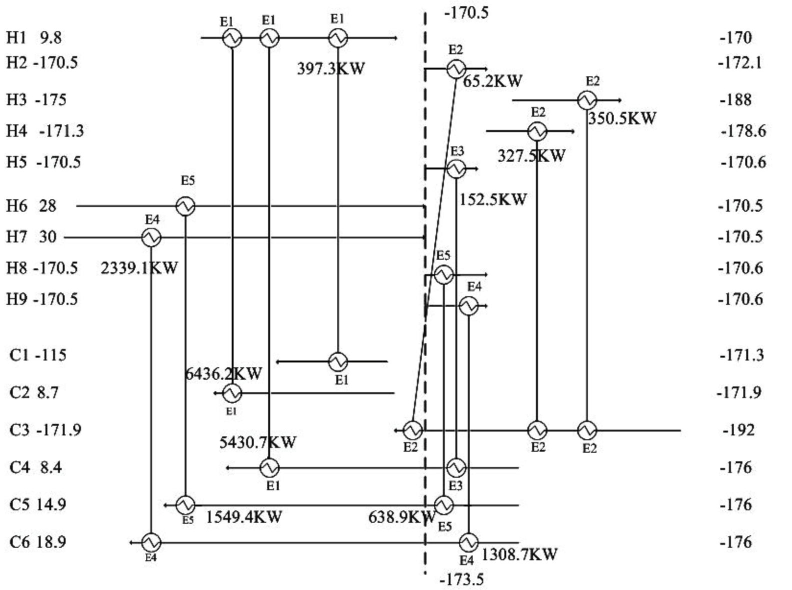

Figure 6. Heat network of the modified ASU process

In the pinch calculation, a part of cooling capacity is provided by the expansion turbine. And no other variables are affected by turbines. Thereby the expansion turbine can be equivalent to the cooler. In ASU process the phase transition often takes place. Large quantity of latent heat greatly influences the position of pinch point. Thus the effect of phase transition must be considered. The stream in which phase transition takes place should be split especially when the phase transition takes place near the pinch point.

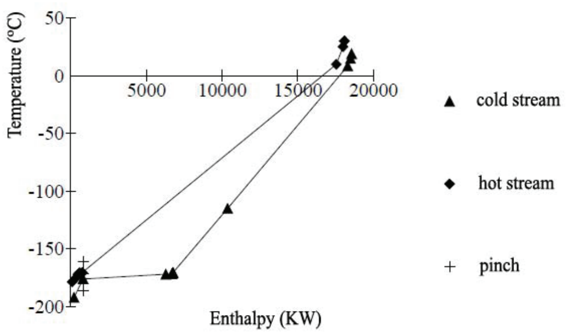

Figure 7. Compound curve of streams

As shown in Fig.7, it is indicated that the average pinch point is -172℃. And the minimum pinch temperature difference is 3℃. All streams can be matched and all the heat can be recovered. All cooling captivity can be provided by expansion turbine. The results of pinch calculation agree well with the industrial data. Compared the improved process with the actual process, energy consumption can be reduced by 7.55MW. Meanwhile the oxygen product will be increased by 2011 Nm^3/h. Therefore the total energy efficiency can be raised by 27.21%.

4. RESULTS AND DISCUSSION

The full low pressure process is adopted. Thus compression work can be reduced. It is found that the inlet flow rate of the air compressor is abnormal. The design value of flow rate is 169291Nm^3/h, and the real value is 150000Nm^3/h. Thereby, the feed stream of column C1 will be reduced. But the needs of nitrogen product are increased. In this case the nitrogen product extracted from the top of column C1-C1 has to be raised. Then the flow rate of oxygen-enriched air liquid decreases. Consequently the reflux flow rate of the upper column C1-C2 is reduced. And the purity of oxygen product decreases to 97.4%. Here the design value is 98%. This data proves that the status of distillation becomes deteriorated. It is also found that the central temperature of the main heat exchanger E1 is higher than the design value. This phenomenon points out that the refrigeration loss of the main heat exchanger is overweighted. That is because of local scaling of flow channels.

The magnitude of the exergy loss from each unit is in the order of the main heat exchanger, distillation column, high pressure cycle and expansion turbine. The main reason of exergy loss in E1 is the growth of temperature difference in the cold-side. The pressure drop in the heat exchanger is another reason. To reduce the exergy loss, the air feed flow rate should be increased to design value. Also the temperature differences and pressure drop need to be reduced. The exergy consumption of distillation is in the second place. To obtain better performance, the structure packing method should be adopted instead of the original sieve tray method in the C1-C2 column. It is indicated that structure packing is especially suitable for the upper column in the cryogenic process. For high pressure cycle, the expansion process shows better performance than the original one. It is also found that exergy loss can be reduced when the inlet flow of throttle valve is in the liquid phase. Therefore it is a better choice to increase the subcooling degree. The exergy loss of expansion turbine T1 is related to mechanical efficiency. Thus equipments with higher efficiency need to be used.

Then the pinch calculation is done for the modified process. There is only one stream that goes across pinch point in Fig.6. But the power capacity of heat transfer is very small. And all streams have been matched in this network. The overall performance is not detracted by such one stream. It will be difficult to split any one of the flows. Thereby the stream across pinch can be ignored. According to the results of pinch calculation, the inter-stage cooler of compressors and E7 cooler are both above the pinch point. Therefore the inter-stage thermal energy can be recycled to heat the boiler feed water instead of low pressure steam. Respectively, the E7 cooler can be removed.

Finally, the unified principles which can be widely used in air separation process for energy-saving are summarized. 1) The temperature differences should be reduced, especially for the cold-side temperature differences, thus the exergy loss can be reduced; 2) To reduce the resistance of the upper column as much as possible, the structure packing column is effective; 3) The throttle valve should be arranged when the working fluid is at the liquid state, and the higher the subcooling is the smaller the exergy loss is; 4) The effect of phase transition should be considered and the expansion turbine can be equivalent to the cooler in the pinch calculation; 5) Use expansion turbine instead of expansion valve whenever possible; 6) The optimization of ASU can be summarized as a MINLP model which can be solved by multi-objective GA and LP algorithm; 7) Compressor inter-stage thermal energy can be recycled to heat the boiler feed water.

5. CONCLUSION

The conclusions of the study can be drawn as follows.

- According to the simulation analysis, the new air separation process is proposed for energy saving.
- The optimization of such process can be solved by a novel algorithm in which the multi-objective genetic algorithm and linear programming are combined. Therefore the problem with multi-objective, multi-constraint and integers mixed will become easier to be studied.
- Seven unified principles which can be widely used in air separation process for energy-saving are summarized.

NOMENCLATURE

DVF	designed volume flow-rate	(Nm^3/h)
RVF	real volume flow-rate	(Nm^3/h)
PD	percentage of deviation	(%)
Ex	exergy	(kW)
H	enthalpy	(kW)
T	temperature	(K)
S	entropy	(kW/℃)
η	exergy loss ratio	(–)
Rx	gas-liquid ratio	(–)
G	gas fraction	(Nm^3/h)
L	liquid fraction	(Nm^3/h)

Subscripts

0	environment
loss	exergy loss
in	inlet flow
out	outlet flow
Δ	change

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