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Aqueous ammonia solution cooling absorption refrigeration driven by fishing boat diesel exhaust heat

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Abstract: A solution cooling absorption (SCA) approach is proposed to modify the aqueous ammonia absorption refrigeration cycle using the strong solution from the absorber to cool the forepart of the absorption in the cycle for reclaiming some portion of absorption heat. As a consequence of raised temperature at the inlet, the strong solution partially boils at the outlet of the solution heat exchanger, and diminishes the thermal heat consumption of the heat source. The calculation results show that the coefficient of performance (COP) of this modified cycle is about 28.3% higher than that of the traditional cycle under typical conditions; while the required heat transfer area of the total heat exchangers of the cycle is somewhat less than that of the traditional one. The capacity of refrigeration with the new absorption cycle is more than doubled in contrast to the adsorption scheme with an identical configuration. It is sufficient to supply a fishing boat the chilling capacity for preservation of fishing products with the modified cycle chiller driven by its diesel engine exhaust.

Key words: aqueous ammonia absorption refrigeration; solution cooling absorption; waste heat recovery; heat and mass transfer; coefficient of performance

In China, the offshore fishing boats are generally small or medium sized vessels without a refrigerator, so they carry lump ice for the preservation of fishing products. As the freshness time of the fishing products with lump ice is short, the fishing boats need to frequently come and go between the fishing field and the base harbor. Thus, it not only requires high cost for ice and fuel oil, but also causes inconvenience and wastes time. Nevertheless, about 30% to 50% of fuel heat is dissipated into the atmosphere in the form of high-temperature exhaust gas from the diesel engine. If this heat resource is used to drive a refrigerator, it can solve the problem of fish preservation without increasing fuel consumption. The economic benefits are significant in saving the cost for ice and oil, catching more fish each time, and raising fish prices due to higher quality, and so on.

The compression refrigerators are far more popular than the absorption refrigerators due to advantages such as compactness, lightweightness, flexibility, and easy operation. However, for refrigeration in a small fishing boat, the compression refrigerator is not suitable since it needs an additional diesel engine to drive, which also consumes oil. Like a compression refrigeration cycle, the aqueous ammonia absorption refrigeration cycle is operational on the evaporation of refrigerant (ammonia) at low temperature. However, after evaporation, low-pressure ammonia vapor does not enter a compressor to raise the pressure but enters an absorber instead, and it is liquefied through an absorption process of weak solution and dissipates heat to the cooling water. Then, at the outlet of the absorber the produced strong solution is pressurized by a solution pump. By absorbing thermal heat, high-pressure ammonia vapor is produced from the strong solution in a generator. Finally, the vapor is condensed in a condenser and the liquid ammonia reenters the evaporator after throttling to realize refrigeration. In order to improve the cycle efficiency, a solution heat exchanger is usually set up between the absorber and the generator, and also a precooler is sometimes set up before the evaporator. A rectifier is required at the generator outlet to diminish the water vapor content in the ammonia vapor.

The advantages of the aqueous ammonia absorption refrigerators over the compression refrigerators and adsorption ones are as follows: 1) Ammonia refrigerant and water are natural substances, and they have no ozone depletion effects. 2) The absorption refrigeration cycle is a continuous process. 3) The working medium of ammonia-water absorption refrigeration passing through the heat transfer surfaces is liquid and often with a phase change process. Thus, the heat and mass transfer coefficients are relatively high, therefore requiring less heat transfer area, and also the material of the heat exchangers can use low-priced carbon steel. 4) Under the same conditions, the efficiency of the aqueous ammonia absorption refrigeration cycle is much higher than that of the adsorption refrigeration cycle. 5) The capacities of the ammonia absorption refrigerators can vary from a few dozen watts to some megawatts. In fact, in the case of a waste heat reclaim system for below −10 ℃ chilling, the ammonia absorption refrigerator is the most cost-effective machine, even though the traditional ammonia absorption chiller needs to reform and modify its cycle and heat exchangers.

1 Advanced NH_3-H_2O Absorption Cycle

A single-stage absorption refrigeration cycle is the basis of the absorption cycle, and its *p*-*t* diagram is shown in Fig. 1. The cycle mainly consists of condensation, throttling, evaporation, absorption, generation and heat regeneration processes. The pressure of the strong solution at the absorber outlet (state point 4) is raised through a solution pump (4-4a),

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and then the strong solution enters the solution heat exchanger (4a-1), the generator and the rectifier (1-2), where the ammonia vapor is separated from the solution to the condenser (point 5). Then the condensate is throttled to the evaporator for chilling (point 0). While the temperature of the remaining weak solution (point 2) is reduced through the solution heat exchanger (2-2b), and then flows back to the absorber (3-4), where it absorbs ammonia vapor from the evaporator (point 0) and becomes a strong solution (point 4) for circulation.

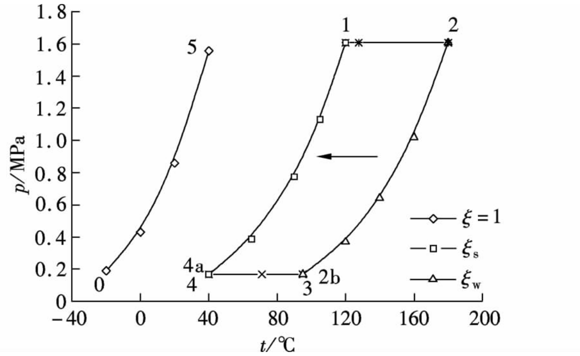

Fig. 1 *p-t* diagram of single stage of NH_3-H_2O absorption cycle

The traditional ammonia absorption chiller is bulky. It occupies far more volume than the lithium bromide absorption chiller with the same capacity, and its coefficient of performance (COP) value is lower compared with its lithium bromide absorption counterpart. To overcome these shortcomings, many researchers[1-4] studied modified cycles such as the generator absorber heat exchange (GAX) cycle. Zheng et al.[5] performed computer simulation on the GAX cycle and the traditional single-stage ammonia-water absorption refrigeration cycle. The results show that in the case of t_2 = 120 ℃, $t_4 = t_5$ = 25 ℃, t_0 = 5 ℃, the COP values of the two refrigeration cycles are 0. 776 and 0. 589, respectively. However, the attempt to use absorption heat in the generation process is applicable only if there is a temperature overlap between these two processes; i. e., the value of $(t_3 - t_1)$, as shown in Fig. 1, should be positive and sufficiently great to transmit heat from the absorption process to the generation process. It restricts the operation condition that the cooling water temperature should be low so that the high pressure P_h of the cycle is low, and the evaporation temperature should be high so that the low pressure P_L of the cycle is high. Simultaneously, the heat source temperature should be high so that the temperature overlap between the absorption and generation processes is great. Therefore, the GAX cycle can only be adopted in an air-conditioning chiller. Calculation shows that, with air-conditioning evaporation temperature t_0 = 5 ℃, if the condensation temperature t_5 and the absorption strong solution temperature t_4 rise to 40 ℃ which is a typical value of an air-conditioning chiller, the generation outlet temperature t_2 should be greater than 150 ℃ to complete the GAX cycle, with a COP value of about 0. 72. Nevertheless, a COP value of about 1. 2 can be obtained if a lithium bromide absorption chiller is used under the same conditions. Thus, in the air-conditioning temperature domain, the lithium bromide absorption refrigeration is far more competitive than the ammonia absorption refrigerators in the marketplace. However, the advantages of the ammonia absorption refrigerators lies in that they can be used below the freezing point, and, thus, the NH_3-H_2O GAX cycle is not a practical and useful cycle. Moreover, regarding the heat exchanger structure, the GAX heat exchanger is supposed to achieve the absorption process on the one side and the generation process on the other side of the heat exchanger at the same time with counter-flow configuration, which is difficult to realize, as in either process the fluid undergoes a phase transition.

When the evaporation temperature is lower than −10 ℃, there is no temperature overlap between the two aforementioned processes. On the other hand, as the absorption process usually has about a 20 to 50 ℃ temperature difference, the heat is dissipated at a higher temperature at the front section than at the rear section in the absorption process. So the front section can be cooled by the strong solution from the outlet of the absorber via a pump. Such an approach is named as solution cooling absorption (SCA). As a consequence, the heat transmitted to cooling water is reduced correspondingly in the absorber. And, because of the raised temperature before entering the solution heat exchanger from the endothermic solution cooling absorption, the strong solution at the outlet of the solution heat exchanger will reach the two-phase region after picking up the heat of the weak solution on the other side, which means that a portion of the generation process is heated by the weak solution. By reducing the demand for external heat in the generator, the COP value can be considerably increased.

Refering back to the refrigeration for a fishing boat, as the temperature of the diesel exhaust gas is relatively high, the SCA single-stage ammonia absorption refrigeration cycle is applied. The SCA single-stage cycle, as shown in Fig. 2, consists of evaporation (0), condensation (5), solution heating generation (1-1a and 2-2a), external heating generation (1a-2), solution cooling absorption (3-3a and 4a-4b), external cooling absorption (3a-4), pumping (4-4a), and heat regeneration (2a-3 and 4b-1). The rectification and precooling processes are not shown in the *p-t* diagram.

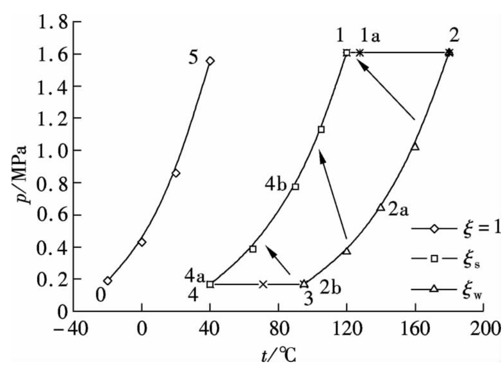

Fig. 2 *p-t* diagram of single stage of SCA cycle

2 Equipment Modification

The absorption chiller consists of several heat exchangers. Their performance is also crucial to the performance of the refrigerator. We have improved the structure of the ammonia absorption refrigerator to make it compact, efficient and cheap[6-7]. Fig. 3 shows the schematic flowchart of the SCA aqueous ammonia absorption chiller for a fishing boat driven by diesel exhaust gas. The traditional ammonia absorption refrigerators usually use vertical shell and tube generators together with the rectifier column and the tube-coil dephlegmator one above the other, so the overall height of the chiller may be too high. Considering the heat source is diesel exhaust gas, the fin-tube bundle is adopted to extend the outside surface area of the tubes for the generator, and the fin tubes are connected with two stages of manifold tubes to distribute the solution from the inlet tube to each fin tube of the tube bundle and then converge to the outlet tube. With the combination of the rectifier column in parallel, the generator plays a role of a reboiler, and natural convection can be circulated. This direct heating scheme is simpler in structure and more efficient than using a third medium or heat pipes to transmit heat from the exhaust gas to the working medium.

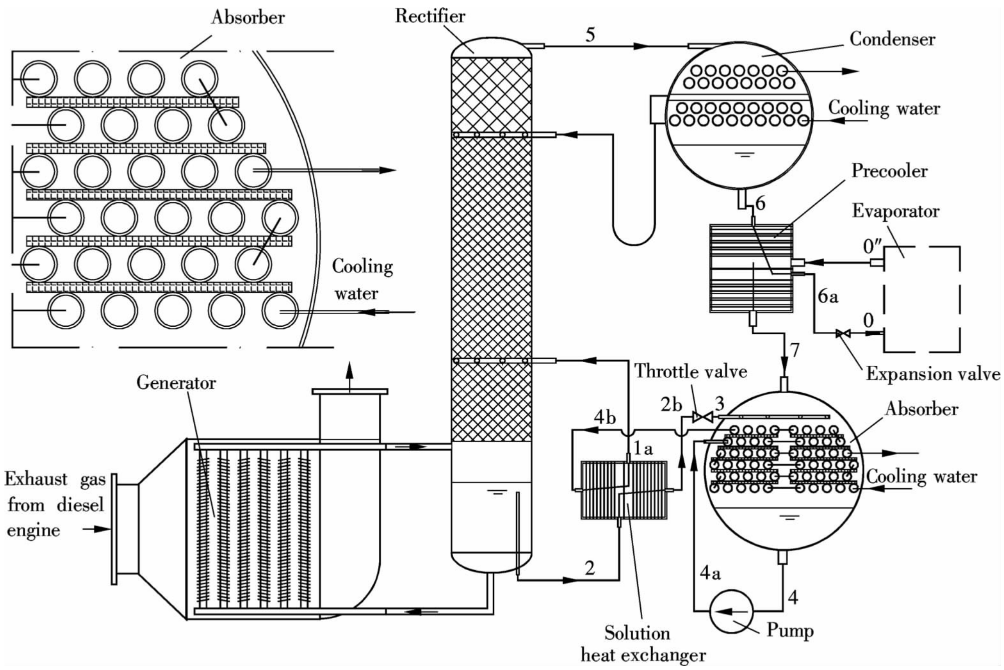

Fig. 3 Schematic diagram of the SCA single-stage ammonia-water absorption refrigerator

The shell and tube heat exchangers are adopted for the absorber and the condenser to facilitate regular cleaning of the sea water side tubes. The authors propose an enhanced heat and mass transfer technique that puts stainless steel mesh packing between the staggered tube rows in the absorber, as shown in the zoom chart in Fig. 3. The stainless steel mesh packing not only adds some dual-side exposed surface area to the refrigerant vapor, but also leads the solution from the upper tubes to the lower tubes with film-inversion and mixing effects, which are very effective in enhaning the absorption process. As a small capacity chiller, the heat transfer surfaces of the solution cooling absorber are included in the same shell vessel of the external cooling absorber for compactness. The tubes of the solution cooling absorber are arranged above the tubes of the external cooling absorber to realize countercurrent heat transfer. Since it is heated in the solution cooling absorber, the strong solution is too hot to be re-used for cooling in the rectifier. Consequently, the rectifier requires external cooling, which is either to use a dephlegmator or to lead some condensate from the main condenser to the rectifier. By setting up a condensate collection tray at the upper part of the main condenser, a certain portion of the condensate is led back to the rectifier by gravity. Thus, the number of heat exchangers is reduced or an ammonia pump is saved. As the proportion of the condensate from the collection tray is fixed, the appropriate condensate return ratio can be automatically guaranteed. Both the precooler and the solution heat exchanger are of spiral plate heat exchangers, not only for compactness, but also for achieving countercurrent heat transfer with a relatively small volumetric flow rate of the solutions. As the solution heat exchanger includes a solution heating generation surface at the center semicircular chamber of the spiral plate heat exchanger, the vapor-liquid mixture can be led through a connection pipe into the rectifier column. Moreover, because the refrigerant is ammonia, direct evaporation is adopted to supply fishing storage vessels with the chilling capacity of fanned coolers or coils, in order to improve efficiency, simplify the system and reduce both initial and operational costs.

3 Heat and Mass Balance of the SCA Cycle

It can be seen from Figs. 1 and 2 that there is no difference between the quadrilateral vertex points of the SCA cycle and those of the traditional cycle. Only the solution heat regeneration processes of the two cycles are different. The parameters of the quadrilateral vertex points 1 to 4 of the cycle can be obtained first from the temperatures of the heat source, cooling water and evaporation, and the pinch temperature difference for each heat exchanger. The enthalpy of the weak solution at the outlet of the solution heat exchanger (point 2b) is assumed to coincide with that at the vertex point 3 of the cycle.

The special calculations related to the SCA cycle are intended to determine the two-phase region parameters of points 1a and 3a as well as the single-phase solution points 2a and 4b, as shown in Fig. 2. The calculation steps are:

1) To determine the temperature at point 4b by subtracting the pinch temperature difference for heat transfer from the temperature at point 3;

2) To determine the parameters at point 3a by the heat and mass balance calculation of the solution cooling absorber;

3) To obtain point 2a of the weak solution, which corresponds to point 1 of the strong solution on the other side of the solution heat exchanger by single-phase section heat balance (4b-1/2a-2b), and to check whether the temperature at point 2a meets the requirement of a minimum pinch differential temperature with the vertex point 1;

4) To obtain the parameters at the outlet of the strong solution (point 1a) in the two-phase section of the solution heat exchanger by heat balance with the weak solution.

In the solution cooling absorber, the strong solution goes inside the tubes as the cooling medium, while the weak solution sprays at the out-wall-surface of the tubes; and the coolant vapor permeates the shell-side space. The mass flow with a unit mass of coolant, enthalpy and mass fraction values at the inlets and the outlets of both hot and cold fluid flows are shown in Fig. 4. By assuming the initial value of the mass fraction ξ_{3a}, the mass and energy balance relationships in the solution cooling absorber are obtained by the following equations:

$$f = \frac{\xi''_0 - \xi_w}{\xi_s - \xi_w} \tag{1}$$

$$f_{sca} = \frac{\xi''_0 - \xi_w}{\xi_{3a} - \xi_w} \tag{2}$$

$$h_{3a} = \frac{1}{f_{sca}}\left[(f_{sca} - 1) h_3 + h''_0 - \frac{f(f_{sca} - 1)}{(f-1)}(h_{4b} - h_{4a}) \right] \tag{3}$$

where f is the circulation ratio of the cycle; f_{sca} is the circulation ratio of the SCA section. By comparing the mass fraction ξ_{3a} of liquid at point 3a corresponding to h_{3a} with the assumed initial value, the approximation of the value ξ_{3a} is gradually reached.

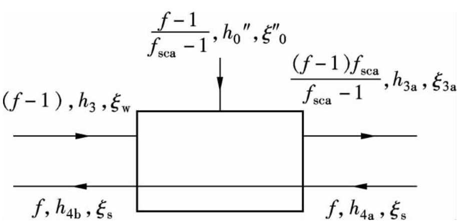

Fig. 4 Heat and mass balance in the solution cooling absorber

The parameters of point 1a at the outlet of the strong solution from the solution heat exchanger are determined by the heat balance with the weak solution from point 2 to point 2a, as shown in Fig. 5. The total enthalpy H_{1a} including both liquid and gas phases is obtained by

$$H_{1a} = h_1 + \frac{(h_2 - h_{2a})(f-1)}{f} \tag{4}$$

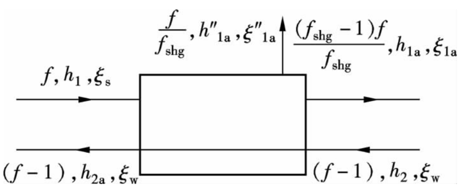

Fig. 5 Heat and mass balance in the solution heat generation section of the solution heat exchanger

As point 1a is at the two-phase region, according to the mass and energy conservation equations, the strong solution side changes from the point 1 with a unit mass flow rate of f and a mass fraction of ξ_s to the point 1a with a vapor-phase mass flow rate of (f/f_{shg}) and a mass fraction of ξ''_{1a}, and a liquid-phase mass flow rate of $[f(f_{shg} - 1)/f_{shg}]$ and a mass fraction of ξ_{1a}.

$$f_{shg} = \frac{\xi''_{1a} - \xi_{1a}}{\xi_s - \xi_{1a}} \tag{5}$$

$$H_{1a} = \frac{(f_{shg} - 1) h_{1a} + h''_{1a}}{f_{shg}} \tag{6}$$

where f_{shg} is the circulation ratio of the solution heating generation (SHG) section; h_{1a}, h''_{1a}, and H_{1a} are referred to as the liquid enthalpy, the vapor enthalpy, and the total enthalpy of the solution at point 1a, respectively. By comparing H_{1a} from Eq. (6) corresponding to the assumed initial value of ξ_{1a} with the value of H_{1a} from Eq. (4), the value of ξ_{1a} can be obtained with the trial and error method.

4 Comparative Analysis of Thermal Coefficient

The mathematical model is based on the application of global mass, species and energy balances. The following assumptions are made: Heat losses to the environment are negligible; pressure losses between the generator and the condenser and those between the evaporator and the absorber are all equal to 20 kPa, while the pressure drops in all the heat exchangers are not considered; the condensed liquid from the condenser and the weak solution leaving the generator are saturated. The Schultz state equations[8] are used for the ammonia-water equilibrium and thermodynamic property calculation.

The design conditional parameters are shown in Tab. 1.

Tab. 1 The design conditional parameters

Parameters	Value
Chilling capacity Q_0/kW	35
Inlet temperature of exhaust gas t_{h1}/℃	350
Outlet temperature of exhaust gas t_{h2}/℃	180
Inlet temperature of cooling water t_{k1}/℃	30
Condenser outlet temperature of cooling water t_{k2}/℃	36
Absorber outlet temperature of cooling water t_{k3}/℃	40
Evaporation temperature t_0/℃	−20

The cooling water is a parallel flow to the condenser and the absorber. According to Fig. 1, the parameter values of the points in the ammonia absorption refrigeration cycle are shown in Tab. 2. From Tab. 3 it can be seen that the COP of the SCA cycle is 28% greater than that of the traditional cycle. The solution cooling absorber uses one heat exchanger to perform cooling of the front part of the absorption and heating of the strong solution simultaneously, eventually reducing area for generator external heat sources. Therefore, although it looks like adding an SCA heat exchanger to the cycle, the overall heat transfer area is decreased, and also the structure of the SCA heat exchanger is simple, as there is no phase change on the strong solution side. Consequently, the actual manufacturing costs can be decreased in comparison with those of the traditional cycle.

Tab. 2 Parameters of the state points of the SCA ammonia absorption cycle

Point	Description	Pressure/kPa	Temperature/℃	Mass fraction/(kg·kg^{-1})
1	Strong solution at the starting point of vapor generation	1 610	116	0. 320
1″	Vapor at the starting point of vapor generation	1 610	116	0. 912
1a	Medium solution at the outlet of solution heat exchanger	1 610	126	0. 281
1a″	Vapor at the outlet of solution heat exchanger	1 610	126	0. 872
2	Weak solution at the outlet of generator	1 610	160	0. 063
2a	Weak solution corresponding to point 1 at the other side	1 610	131	0. 063
2b	Weak solution at the outlet of solution heat exchanger	1 610	95	0. 063
3	Weak solution at the inlet of SCA	170	95	0. 063
3a	Medium solution at the outlet of SCA	170	69	0. 162
4	Strong solution at the outlet of absorber	170	38	0. 320
4a	Strong solution at the outlet of pump	1 610	38	0. 320
4b	Strong solution at the outlet of SCA	1 610	90	0. 320
5	Ammonia vapor at the outlet of rectifier	1 610	50	0. 999
6	Ammonia liquid at the outlet of condenser	1 590	40	1
6a	Ammonia liquid at the outlet of precooler	1 590	14	1
0	Ammonia liquid at the outlet of expansion valve	190	−20	1
0″	Ammonia vapor at the outlet of evaporator	190	−20	1
7	Ammonia vapor at the outlet of precooler	190	33	1

Tab. 3 Comparison of COP of three schemes

Parameters	Traditional cycle	SCA cycle	SC rectifier cycle
COP	0. 448	0. 575	0. 530
Ratio of COP	1	1. 28	1. 18

Tan et al. [9] presented the result of an adsorption chiller with a refrigeration capacity of Q_0 = 12 kW for a fishing boat. The heat load of flue gas to driving the chiller is 71. 2 kW, with a COP of 0. 17. Wang et al. [10] presented a similar result. Nevertheless, the same amount of exhaust heat can drive a chiller of SCA NH_3-H_2O absorption cycle with a refrigeration capacity of over 40 kW, sufficiently to supply a boat with the chilling capacity for fish preservation.

5 Conclusion

For below the freezing point evaporation, the NH_3-H_2O GAX cycle is not practical while the SCA cycle is feasible. The COP of the SCA cycle is about 30% greater than that of the traditional cycle with a reduced overall heat transfer area, which is closely related to the manufacturing cost.

A lot of modifications are conducted on the structure of the SCA NH_3-H_2O absorption chiller. The generator adopts a fin-tube bundle with two stages of manifold tubes. The stainless steel mesh packing is inserted between the staggered tube rows in the absorber to form an alternate heat and mass transfer configuration. A condensate collection tray is set up at the upper part of the main condenser, to lead a certain portion of the condensate back to the rectifier by gravity.

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渔船尾气驱动的氨水溶液冷却吸收式制冷

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摘要:提出了一种溶液冷却吸收的氨水吸收式制冷循环方案,即利用来自吸收器的浓溶液冷却吸收过程的前半部分以回收部分吸收热. 由于进入溶液热交换器的浓溶液温度提高,在其出口浓溶液将部分沸腾,因而可减少外界热源的消耗. 计算结果显示,在典型条件下改进循环的性能系数(COP)比传统循环提高约 28.3%,而该循环所有换热器所需的总换热面积则比传统循环略有减少. 在同等条件下与吸附式制冷方案相比,改进循环的制冷量可增加 1 倍多. 渔船采用改进循环的制冷机后用其自身柴油机废气足以提供渔品保鲜用的制冷量.

关键词:氨水吸收式制冷;溶液冷却吸收;余热回收;传热传质;COP

中图分类号:TK123