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Recent developments of refrigeration technology in fishing vessels

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Abstract

Modern large and fast ocean fishing vessels include mechanical refrigeration, but all of them consume precious fuel or electricity to achieve refrigeration. Fishing vessels with tonnage at about 100 tons cannot attach compressor-icemaker onboard because of their small horsepower of diesel engine. These vessels always have to carry a lot of ice for caught fish preservation. At the same time, waste heat dissipated in the hot exhaust gases in most of the fishing vessels is rejected to the atmosphere. At present, some effort has been devoted to the utilization of the vast amount of the waste energy for refrigeration. In this paper, several types of refrigeration technology in fishing vessels are introduced, such as vapor-compression refrigeration systems, heat recovery systems to power absorption refrigeration plant, adsorption systems for producing chilled water, and adsorption icemaker systems, especially an adsorption icemaker prototype in our laboratory. The better perspectives of applications for the lattermost exist in fishing vessels.

Keywords: Fishing vessel; Refrigeration; Waste heat recovery; Adsorption icemaker

1. Introduction

Since natural ice was used from 1797 for carriage of fish by sailing ships to the UK [1], fishing vessels traditionally used crushed ice for caught fish preservation. The mechanical

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refrigeration system aboard tuna seiners had been developed in the late 1930s for use aboard bait boats [2] and some vessels, less than 30 m size, had been equipped with onboard mechanical refrigeration and freezing in 1960s [3]. A wide variety of the modern large and fast fishing vessels and mechanical refrigerating plants exists today, varying with fish species, size and processing methods [1]. All of these systems consume precious fuel or electricity to achieve refrigeration. However, the fishing vessels with tonnage at about 100 tons cannot carry compressor-icemaker onboard because of their small horsepower of diesel engine. Therefore, they always have to carry a lot of ice to keep their catches fresh when fishermen go fishing on the sea. Their internal combustion engines typically have a thermal efficiency of 40%. At present, most of the fishing vessels do not use any heat recovery system. The remaining energy is rejected to the atmosphere in the form of hot exhaust gases. Much work now in progress is directed to the improvement of the thermal efficiency by achieving better consumption of the fuel. Only a few of them employ an exhaust gas boiler to heat up water for cleaning purposes. Some effort has been devoted to the utilization of the vast amount of waste energy dissipated in the exhaust gases for refrigeration.

Absorption/adsorption systems are heat-operated units that need little electricity, so they can utilize waste heat or renewable energies. There are many possibilities for applications of sorption systems most of which, however, have not reached a significant state of maturity up to today. One of the evergreens, for instance, is the waste heat driven refrigeration system for fishing vessel application. Ziegler [4] discussed current trends as well as forthcoming applications in sorption heat pumping and cooling technologies. Srikhirin et al. [5] described a number of research options of absorption refrigeration technology and provided a comparison of the various types of absorption refrigeration systems. Meunier [6] claims solid sorption is very effective for low grade cooling, not only for air conditioning but also for deep freezing. By employing waste heat discharged from a fishing vessel's internal combustion engine to drive a sorption refrigeration system, the engine shaft can be relieved of the load required by the compressor of a conventional vapor-compression system for the larger vessels, and considerable fuel can be saved. Large space occupied for ice preservation can be avoided and the spoilage of ice may be negligible for the small fishing boats. Another attractive feature is that a sorption refrigeration system is almost noise-free and virtually maintenance-free.

The principal difference between the sorption and the vapor-compression cycles is the mechanism for circulating the refrigerant through the system and providing the necessary pressure difference between the vaporizing and condensing processes. The vapor-compressor employed in the vapor-compression cycle is replaced in the sorption cycle by a sorber and a generator, which compress the vapor as required. The energy input required by the vapor-compression cycle is supplied to the compressor in the form of mechanical work. In the sorption cycle, the energy input is mostly in the form of heat supplied to the generator. In the present case, the heat source is the exhaust heat of a fishing vessel internal combustion engine. Normally, solid sorption systems are preferred to liquid sorption systems. The reasons are mainly the flexibility in attainable temperatures of solid sorption, no need of a rectifying column, the corrosiveness of liquid sorption, the power requirement for the solution pump, and the difficulty for handling liquids in an accelerated, moving and reeling system.

An adsorption refrigerator to produce ice is mainly reported among the adsorptive solar cooling systems with day/night cycle [7–25]. However, Tamainot-Telto and Critoph [26] present the description of a laboratory prototype of an adsorption cooling machine, which uses an activated monolithic carbon–ammonia pair and the steam boiler producing steam from 100 to 150 °C as heat source. The maximum specific cooling power over the whole cycle and the COP (Coefficient of Performance) are 60 W/kg carbon and 0.120, respectively, at icemaker operating conditions corresponding to the evaporating temperature ranging from −20 to 0 °C.

This paper is devoted to recent developments in refrigeration technologies featuring applications for ocean fishing vessels. In the case of a fish storage cooling machine, many investigations (but not all) have been reviewed, with the emphasis on salient experimental achievements including related research in our laboratory.

2. The compression refrigeration system aboard tuna seiners

Since the refrigeration system in use aboard tuna seiners was developed in the late 1930s, fishing methods have changed, vessel carrying capacities have increased tenfold, catch rates have increased fivefold, and individual fishwell sizes have increased fourfold [2]. As a result, although catch rates have gone up, the refrigeration effect per ton of tuna per well has actually gone down. Despite these trends, the current refrigeration system works remarkably well. This is due partly to its inherent flexibility and partly to the durability of the tuna with respect to its intended canned market. Typical seiners have 15–19 fishwells or holds with total volumetric capacity of 1190–1360 m^3. The fish wells are of various sizes ranging from 50 to 106 m^3 volumetric capacities per individual well with an average size of 67 m^3 for a 19-well vessel to 80 ft^3 for a 15-well vessel. The well capacities are thus in the order of 44–94 short tons of fish per well. Each well is lined on the sides and overhead with evaporator coils, and each well is insulated with polyurethane foam. The refrigeration system aboard these vessels is a direct expansion ammonia system powered by reciprocating compressors with condensation provided by vertical-tube, box-type condensers. Receivers are provided below the condensers to contain reserve ammonia. This system uses circulated seawater and brine as the secondary refrigerant to chill and freeze the tuna.

The existing system is a simple single stage ammonia system with seawater or brine acting as the secondary refrigerant. Analysis of the present systems aboard tuna seiners indicates that the ammonia compressor capability is adequate, but that the evaporation ability is the limiting factor in providing adequate refrigeration in the larger fishwells [2]. Of the many options available for achieving greater evaporation capability, the provision of an external chiller, which would refrigerate the seawater or brine in the fishwell was selected.

An existing typical seiner having 32 compressor cylinders installed can usually provide 24 cylinders for the six largest wells, leaving eight cylinders for hotel and holding-refrigeration loads. The new typical operating suction condition with chillers added would be about −12 °C. This is up −8.5 °C from typical current operation of −21.5 °C. It would mean that with chillers added, the compressors would be operating at a much greater capacity of about 7.2 RT/cyl instead of the old 4.2 RT/cyl.

Furthermore, the efficiency of compression would go up. The brake horsepower per refrigeration ton would go down from about 2.05 bhp/RT at −21.5 °C to 1.32 bhp/RT at −12 °C while the net refrigeration tonnage effect per well would actually be increased.

Of the many alternatives which could increase the refrigeration effect per well, Cottrell and Hoyt [2] discuss the addition of an external heat exchanger, called a chiller, to augment the refrigeration effect per well provided by the existing coil evaporators lining the fishwell bulkheads. Available data on refrigeration effectiveness of modern tuna seiners are analyzed and a computer simulation of the system is presented. Their study indicates that current tuna refrigeration systems can be improved. This improvement could result in improved fish quality, an economic benefit to tuna vessel owners, if accomplished through chiller addition.

3. Absorption refrigeration system

Nowadays trawler chiller fishing vessels include mechanical refrigeration to keep the ice from melting fast. The hold capacity ranges from 80 to 150 m^3 and the refrigeration needs from 5 to 10 kW. The hold and evaporation temperatures are 0 and −10 °C, respectively. Ice production is not considered. These fishing vessels are driven by a four-stroke diesel engine whose power ranges from 700 to 1200 kW and one or two auxiliary engines of 50–250 kW. Trawler fishing vessels never stop their main engine when cruising or fishing. Moreover, engine load is rather high and constant for the fishing period and close to full engine load for the onward and return trips. Exhaust gases outlet temperature after turbine ranges from 350 to 420 °C.

Cooling limit temperature for engine exhaust gases has been fixed at 180 °C to provide a wide margin over corrosive acids dew-point. If a heat recovery system is designed to power an ammonia–water absorption refrigeration plant for onboard cooling production, the heat power and the thermal level required range from 10 to 20 kW and 100–150 °C, respectively, which are much lower than the available waste heat and the exhaust gases temperature. Moreover, as absorption refrigeration system's COP is greatly affected by the intermediate sink temperature, where absorption and condensation heat are rejected, onboard systems can profit from using the inexpensive sea water as cooling medium in the absorber and condenser which allows one to maintain low absorption and condensation temperatures and therefore a high system COP.

Fernandez-Seara et al. [27] had built a gas-to-thermal fluid heat recovery system to power an NH_3–H_2O absorption refrigeration plant prototype for the use in trawler chiller fishing vessels, at a cost around 1.5 times higher than the cost of the commercially available compression systems. This prototype can save from 2 to 4% of the total ship fuel consumption. The design, modeling and parametric analysis of the system were presented. Optimal design based on real data was performed and the operating function of exhaust gases by-pass control was obtained.

The schematic diagram of the waste heat recovery system is depicted in Fig. 1. System design involves selection of heat transfer fluid and heat exchangers. Major components of the system are the liquid-to-solution and the gas-to-liquid heat exchangers. The former acts as generator and the latter as economizer. The design also includes a gas by-pass

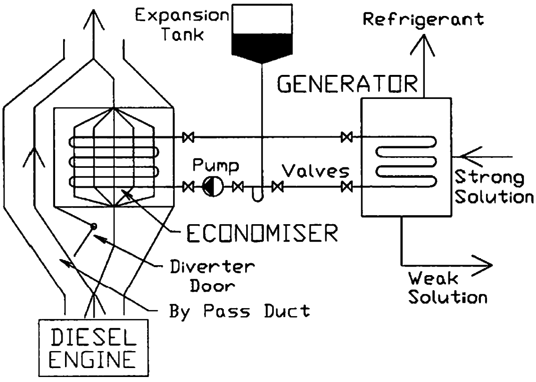

Fig. 1. Schematic of the heat recovery system.

control system and is completed with a pump, piping, expansion tank, valves and insulation material.

Synthetic oil is chosen as the heat transfer fluid and recirculated. The selection has been based on the use of an unpressurized system to reduce the capital and maintenance costs and got a safe and reliable operation. The pump is used to force circulation of fluid at the rate required by the system. The generator of the absorption system is a two-pass kettle type heat exchanger in the bottom of the distillation column, as shown in Fig. 2. The economizer is a gas-to-liquid heat exchanger composed of a finned tube matrix with circular plain fins and staggered layout arranged in series and fitted in the engine stack. The exhaust flow goes either through the finned tubes or the by-pass duct depending on the baffle position (see Fig. 1). The baffle is positioned according to the prototype control system feedback, to maintain the required generator temperature. If the actual temperature is lower than the required generator temperature, the baffle will open, increasing the gas mass flow through the economizer.

Fernandez-Seara et al. [27] had calculated a practical application based on real data taken from a typical trawler chiller fishing vessel using the implemented models. Assuming the cooling duty and the COP of the prototype to be 8.33 kW and 0.5, respectively, the heat power to be recovered is 16.66 kW. The analysis of the results showed that trawler chiller fishing vessels are adequate for installation of ammonia–water absorption refrigeration plants for onboard cooling due to low refrigeration needs at a medium temperature level and appropriate operating conditions of the engine. The high and constant engine load maintained during the fishing period allows the recovery of heat

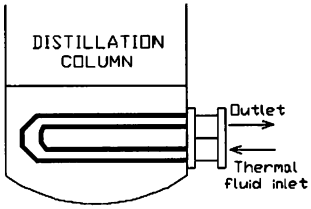

Fig. 2. Two pass kettle type generator.

from engine exhaust at a thermal level that exceeds that required to power the absorption system. Results obtained from simulations of the system and the design of a practical application from real data showed the feasibility of employing this type of heat recovery system in the case studied.

4. Adsorption system for producing chilled water

Generally, a high temperature heat of above 200 °C could be used to power any absorption chilled water system, which has such advantages as continuity of operation, higher COP and extended capacity. However, it is difficult to use an absorption system on a smaller fishing boat because absorption systems have complex components, large volume, high initial costs and are inconvenient to control. In particular, all four main components in the system (generator, condenser, absorber and evaporator) have a free liquid level, and are thus unsuitable for the reeling of the hull. Refrigeration equipment for a fishing boat is required to be as simple as possible and very reliable. On these points the adsorption system is better than any other. The load for preservation on a fishing boat is not fixed, thus making the drawback of intermittent operation less obvious.

Having a good adsorption behavior and requiring a high temperature (above 150 °C) to achieve a regeneration process, a zeolite–water system has a satisfactory refrigeration capacity and is suitable for use where a high temperature heat sources is available. In view of the fact that on a fishing boat, the high temperature heat of the exhaust gas from the diesel engine can be utilized directly (its temperature is up to 400 °C and the available temperature is up to 200–300 °C), Zhu et al. [28] chose this system to refrigerate aquatic products since one method for preserving aquatic products is to put them in chilled seawater at about 5 °C.

Fig. 3 shows the scheme of the adsorption chilled-water system. Zeolite/13X-H_2O is used as a working pair and the exhaust gas from a diesel engine is utilized as a heat source. Because of the intermittent process, two zeolite adsorption units 4a and 4b are arranged in the system. Each unit consists of a generator, a condenser/evaporator and a water tank. The configuration of the generator is similar to a shell-and-tube heat exchanger. Zeolite molecular sieve fills the shell. Some tubes are extended into the shell-plates, which are welded to the shell at each end. The condenser/evaporator, which is finger-shaped, is connected to the shell with a vapor line and immersed in the tank. The tank, the shell and the vapor line are covered with insulating material. With exchange-valve 2, the two units can intermittently alternate their functions with each other. For each unit, when the desorption process is over, the cooling water is cut off by magnetic three-way valve 5, valve 7 is opened to empty the cooling water in the tank, and then fill the tank with water from storage 11. In the adsorption process, the water in the tank stays put, and is stirred by a stirrer to enhance heat transfer; while its temperature reduces to the value required (2–5 °C), valve 6 is opened to let the chilled water go down into the store in which aquatic products are preserved.

The refrigeration capacity of a medium-size prototype for adsorption chiller made was designed as 3500 kJ per cycle. The sample testing was done under real operating conditions (i.e. the unit connected to the diesel engine and heated by its exhaust gas).

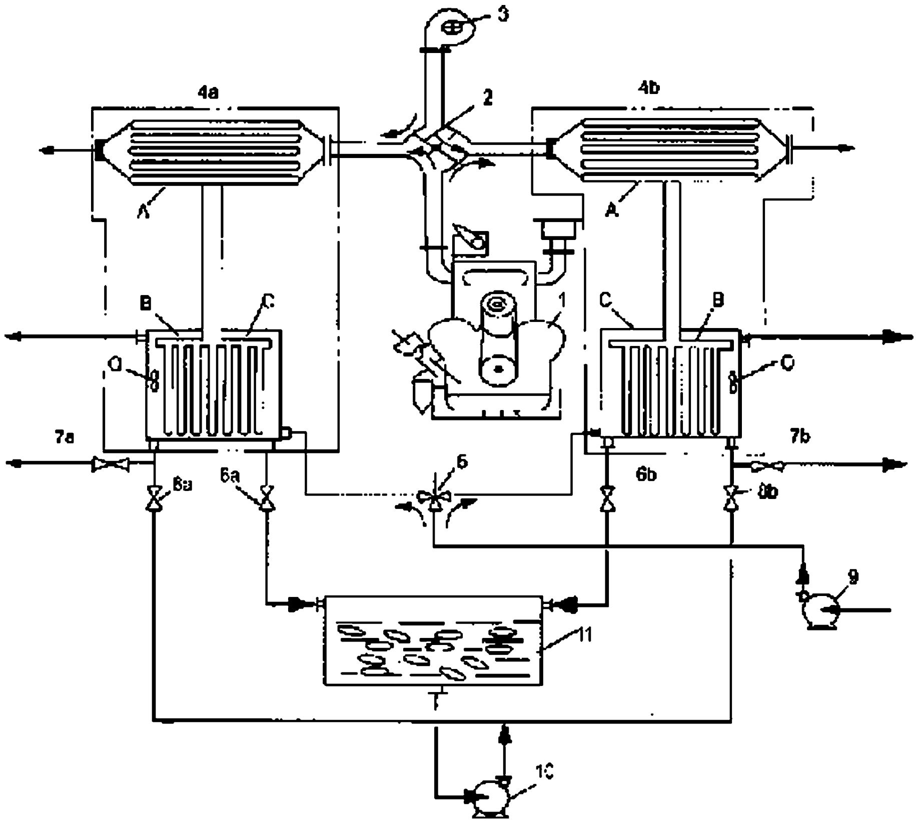

Fig. 3. Scheme of the adsorption chilled water system: 1, diesel engine; 2, exchange-valve; 3, blower; 4a, 4b, zeolite adsorption unit (A, generator; B, condenser/evaporator; C, tank; D, stirrer); 5, magnetic three-way valve; 6a, 6b, 7a, 7b, 8a, 8b, valves; 9, 10, pumps; 11, fish storage.

Preliminary test results showed that when the exhaust gas temperature becomes higher as a result of increasing the engine's load, the capacity of the unit increases or the cycle time shortens, resulting in size, weight and initial cost reduction of the adsorption system to a minimum.

5. Chemical reaction icemaker with exhausted gas

DY fishing vessel diesel engine exhaust icemaker [29] is the refrigeration equipment mainly designed for fishing vessels with tonnage about 100 tons. It takes DY double salt as absorbent and ammonia as refrigerant. Based on chemical affinity, chemical reaction is monovariant and chemical changes occur which induce modification of the solid itself. It is powered by exhaust heat of diesel engine to make flake ice and there is no any increase in consumption of oil.

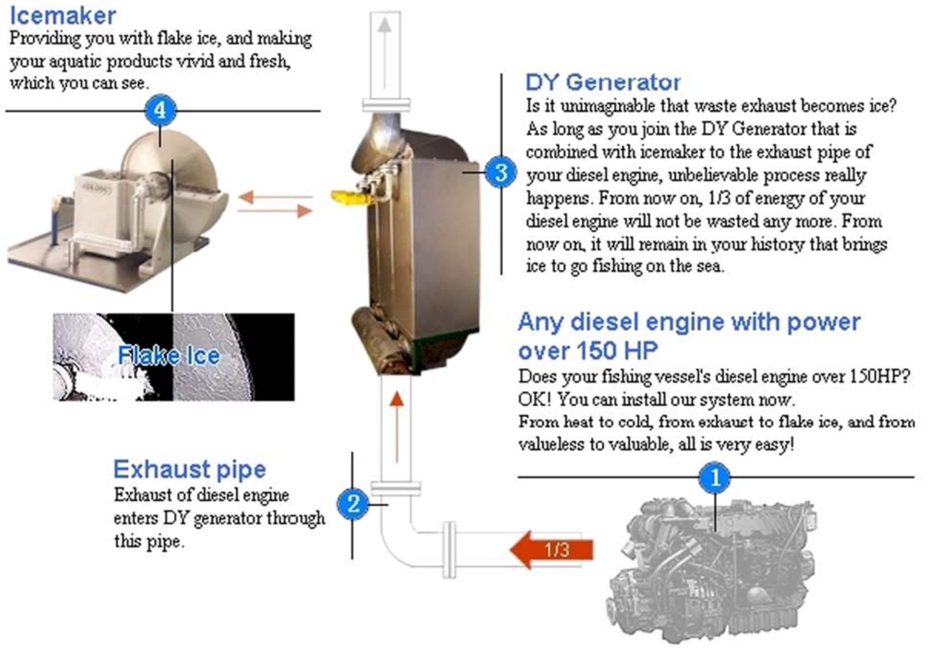

Fig. 4. The structure of the system.

The whole set of DY fishing vessel diesel engine exhaust icemaker includes one ice-maker, one condenser and one DY generator system (see Fig. 4). One DY generator system contains one DY generator, one ammonia tank, one refrigeration control equipment and one exhaust control equipment. The method of chilling uses fresh water or seawater. Ice-making capacity with thickness about 1.5–2 mm is 33–38 kg/h with the ice temperature of −15 °C around.

6. Adsorption icemaker in our laboratory

Water cannot be the working fluid of an icemaker because of its melting point and the temperature of the evaporator could not be less than 0 °C, as would be required in order to freeze water outside the evaporator. Methanol is a good working fluid for an icemaker because it has a high normal boiling point (64.7 °C) and a low melting point (−93.9 °C). Thus, an adsorption system using it as adsorbate can produce a temperature below 0 °C although its latent heat of evaporation (about 1100 kJ/kg) is only half that of water.

With methanol, the machine is always at pressures lower than atmospheric. This is also an important safety factor because it means that, when there is a leak, air comes into the machine and can be detected by an abnormal increase in pressure and poor performance. There is thus adequate warning before methanol can flow out of the pipes.

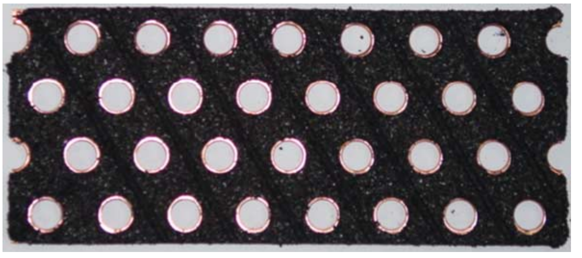

Fig. 5. Photograph of the consolidated carbon block.

Activated carbons have a significant volume of micropores, of convenient size. Activated carbon + methanol seems to be a good pair for a waste icemaker. The selected carbon was the coconut-based one produced by the JVHQ Co. (China). In order to have a better performance, consolidated adsorbents are produced from the granular carbon in our laboratory by collaboration with Hubei Dengfeng Heat Exchanger Co. (China). The form of carbon blocks proposed is as in Fig. 5. The shape is in the form of a cuboid with $272\times116\times10\ mm^3$. The mass of the sample is 0.1385 kg. The bulk density of the block is $600\ kg/m^3$. An adsorber configuration is designed as a shell and tube arrangement in which the shell side with highly internally finned is adsorbent and the tubes contain pressurized heat transfer fluid. Each adsorber in the shape of cuboid contains about 56 kg of carbon.

A two-bed adsorptive prototype ice-making machine operating with a heat and mass recovery cycle has been recently made and tested to use in fishing vessels, as shown in Fig. 6 [30]. The main components are two adsorber, an evaporator, a condenser, a gas–water heat exchanger, a hot-water tank and a flake icemaker (the COLDISC icemaker made by North Star Ice Equipment Co.). An oil burner is used as the simulated heat source from the engine exhaust gas for desorption. The fume gas from the burner heats the water in the hot-water tank through the gas–water heat exchanger. For a detailed description of its working process, see Ref. [31]. Following initial experiments, the cycling time chosen was 40 min including the heat and mass recovery time of 1.5 min. It allows heating and desorption time of 20 min, which corresponds to the optimum heat input for maximum cooling power. That time corresponds to the maximum of the rate of concentration change averaged over time. The results of this system show that a SCP (Specific Cooling Power) of 27 W/kg carbon and a COP of 0.18 have been achieved to produce 18–20 kg/h of flake ice at temperature −7 °C around.

7. Conclusions and future work

Classical vapor-compression technologies have reached a significant state of maturity up to now. A wide variety of the modern large and fast fishing vessels include mechanical refrigeration today, varying with fish species, size and processing methods. All of these systems consume precious fuel or electricity to achieve refrigeration. Along with a consideration for energy efficiency, increasing attention is being given also to the use of waste heat. Absorption/adsorption systems are heat-operated units that need little electricity, so they can utilize waste heat or renewable energies.

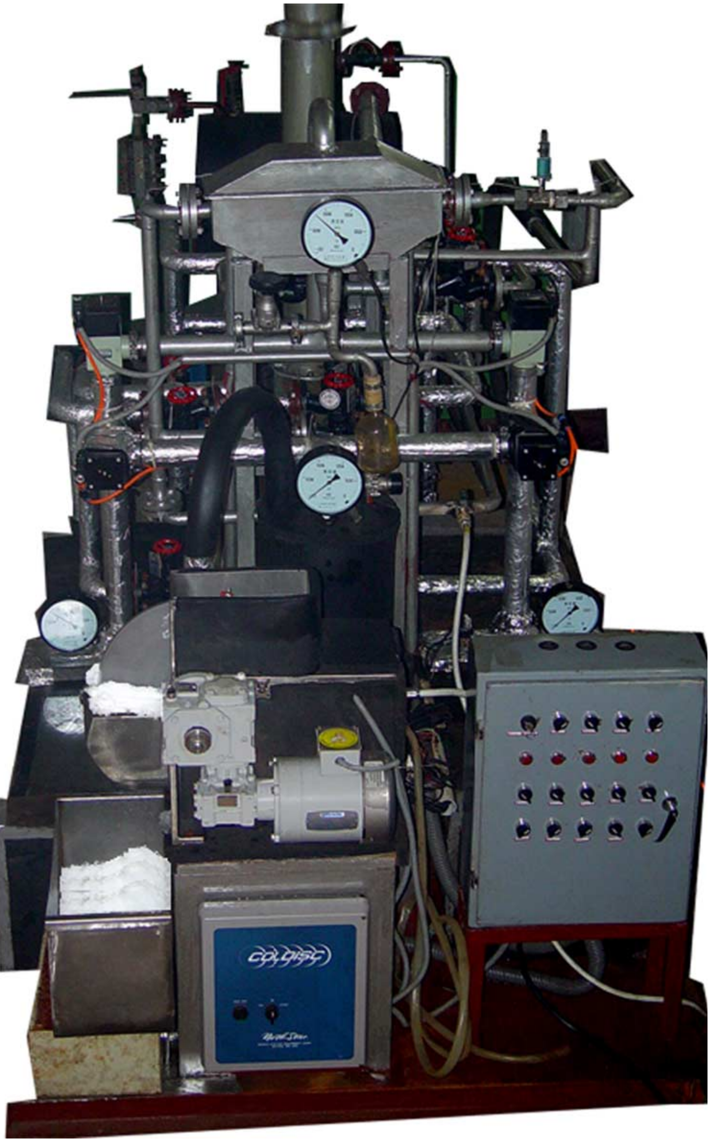

Fig. 6. A adsorption icemaker prototype.

Absorption technologies using lithium bromide–water are fairly well developed and have already been in use for many years but water–ammonia systems have considerable scope for improvement and applications in many countries. Research results have shown the feasibility of employing a gas-to-thermal fluid heat recovery system to power a NH_3–H_2O absorption refrigeration system for the use in trawler chiller fishing vessels.

Adsorption technologies for refrigeration and heating purposes are rather recent. There has been intensification of research during the current decade to develop more efficient solid-adsorption refrigeration systems. Research has shown that solid-adsorption technology has a promising potential for competing with conventional absorption and vapor-compression technologies. The commercial solid–vapor adsorption systems are still non-existent. To this date, adsorption refrigeration systems used for ocean fishing vessels are also under laboratory testing stages. So we find only laboratory experiments of sorption machines in the open literature. As a result of the COP measurements, cycle calculations and estimates of the available heat in the exhaust gases, an adsorption system for fishing vessel refrigeration and ice-making seems to be a more interesting alternative for ocean operating conditions. Moreover, in the case of waste heat recovery, the problem of efficiency is not important for environmental impact since there are no emissions of greenhouse gases.

A two-bed adsorptive prototype ice-making machine operating with a heat and mass recovery cycle has been recently built to use in fishing vessels. The initial test results show that a COP of 0.18 has been achieved to produce 18–20 kg/h of flake ice at temperature −7 °C around. Our future work will design and eventually build an optimized continuous adsorption icemaker performing actually in ocean fishing vessels.

Acknowledgements

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