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ADSORPTION COOLING AS A PROMISING METHOD OF WASTE HEAT UTILIZATION IN SHIP TECHNOLOGY

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Abstract

This paper presents the possibility of practical use of the adsorption cooling method in the shipbuilding technology allowing for the conversion of low temperature waste heat (at approx. 60°C) coming from e.g. main engine cooling water. This work describes the construction and operation of such a device, the characteristics of typical adsorbent-adsorbate combinations, the advantages of such solution and the mathematical model.

Keywords: *Adsorption cooling*

Nomenclature

m_{ads} $[kg_{adsorbent}]$ - the mass of adsorbent in a single absorber

w $\left[\frac{kg_{adsorbate}}{kg_{adsorbent}}\right]$ - level of adsorption

c_{pa} $\left[\frac{J}{kg \cdot K}\right]$ - the specific heat of adsorption

c_{pg} $\left[\frac{J}{kg \cdot K}\right]$ - the specific heat of adsorbate (working fluid in the adsorbed phase)

c_{pv} $\left[\frac{J}{kg \cdot K}\right]$ - the specific heat of adsorbate (working fluid in vapour phase)

ΔH $\left[\frac{J}{kg_{adsorbate}}\right]$ - entalpy of adsorption

r_{skr} $\left[\frac{J}{kg_{adsorbate}}\right]$ - heat of condensation

r_{par} $\left[\frac{J}{kg_{adsorbate}}\right]$ - heat of vaporization

T_{skr} $[K]$ - condensation temperature

T_{par} $[K]$ - evaporation temperature

1. Introduction

The need to save energy resources, improve the energy balance of ships, ocean environment protection and improvement of waste heat economy on the ship are the current engineering problems of modern shipbuilding. In order to meet these challenges and possesses a considerable interest of ship-owners is heat recovery technology based on heat of adsorption effect. Due to environmental concerns and the strict requirements of the MARPOL Convention (Appendix VI) [1] relating to the harmful substances issue, adsorption cooling is an attractive field for research compared with traditional systems using undesirable substances (eg. CFCs). Working fluids used in adsorption cooling devices (e.g. Water, methanol) are environmentally friendly and do not damage the marine environment or the earth's ozone layer. A characteristic feature of adsorption cooling devices is their simple design, allowing for ease of use and maintenance, no moving parts (except circulating pumps for cooling/heating or electro valves) which affects practically no vibration, no use of hazardous materials and practical no corrosiveness. The main disadvantages of adsorption cooling is discontinuous operation, high design requirements for maintaining a high vacuum, large size and weight compared to conventional cooling devices and low values of the coefficient of performance COP. Because of the low COP these installations are preferably powered by waste heat [2]. Research on adsorption cooling devices have helped to significantly increase the efficiency of their work. Application of new sets of adsorbent-adsorbate and modifications to the design of these devices cause the continuous improvement of their efficiency [3], [4].

2. Principle of operation

The absorption chiller consists of 4 main components: evaporator, fields filled with adsorbent, the condenser and the throttle valve. The principle of operation of the adsorption refrigeration apparatus will be described using an example of a simple device constructed of two adsorbers (Figure 1)[5]. Operation of the system can be shown also by the thermodynamic state of absorbers presented in the Clapeyron diagram (Figure 2) [2, 3, 6, 7, 8]. Full cycle consists of four stages: heating the bed, desorption and regeneration, cooling, adsorption. During the heating stage (A-B) adsorber with bed is heated with saturated adsorbate (e.g. waste heat of cooling water coming from the main engine) resulting in increased pressure and temperature. After reaching the condensing pressure (point B) starts desorption process. When the bed is completely regenerated (point C) this stage is completed. In a next step (C-D) the adsorber is cooled, that results decrease of temperature and pressure. When the pressure drops to the evaporation pressure (point D), begins the adsorption process accompanied by release of the heat Q_a.

Adsorbate vapor formed by the evaporation of the working fluid in the evaporator connected to the adsorber. Evaporation results in liquid that evaporates lowering the temperature, thereby obtaining a cooling effect. The ratio of the amount of heat received by the evaporation of the amount of heat supplied to the heating step and the desorption of bed coefficient of performance COP [2]:

$$COP = \frac{Q_p}{Q_o + Q_d} \tag{1}$$

where Q_p – heat of vaporization, Q_o – heat rejected , Q_d – heat supplied.

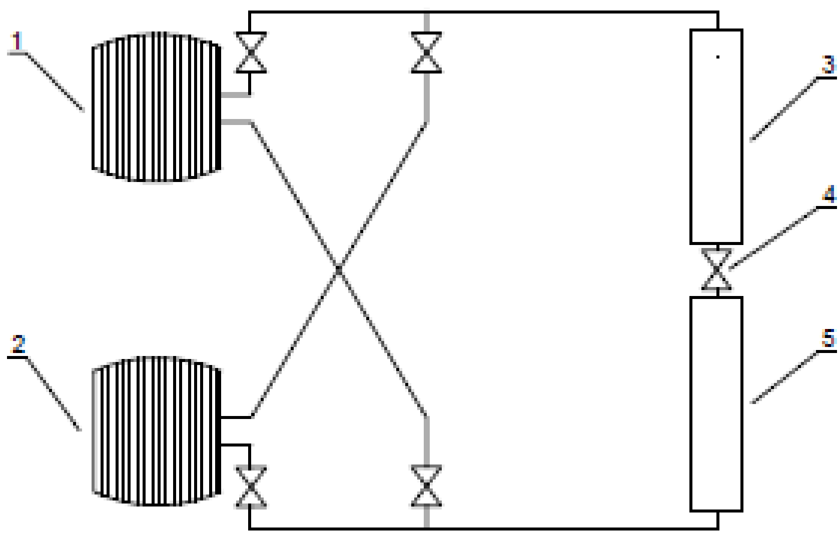

Fig. 1. Absorption refrigeration chiller with two adsorbers: 1 - adsorber, 2 - adsorber, 3 - condenser, 4 - throttle, 5 - evaporator [5]

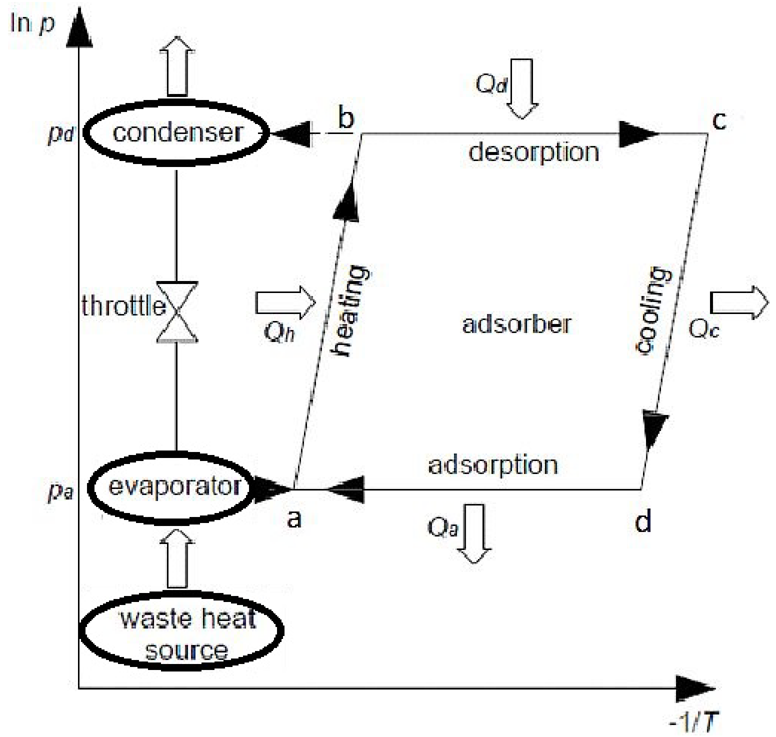

Fig. 2 The adsorption cooling cycle [2, 3, 6, 7, 8]

3. Mathematical model

Inside the adsorption cooling apparatus many different processes occurs. Knowing the relationship between them and the properties of the substance (absorber) can be described in mathematical method behaviour of the device. In the paper presents a generalized mathematical model based upon the model Cacciola and Restuccia and Grzebielec [5, 9]. The model illustrates the heat balance of the adsorption cooling apparatus with a uniform temperature in the bed of adsorbents at a point in time.

3.1. Heat balance of adsorber no.1 (curve A-B-C in Fig. 2)

$$Q_{diz} = m_{ads} \int_{T_A}^{T_B} \left(c_{pa}(T) + c_{pg}(T) \cdot w_{\max} \right) dt \tag{1}$$

$$Q_{ddes} = m_{ads} \int_{w_{\max}}^{w_{\min}} \Delta H(w) dw \tag{2}$$

$$Q_{dog} = m_{ads} \int_{T_B}^{T_C} c_{pa}(T) dT \tag{3}$$

$$Q_{dogg} = m_{ads} \int_{T_B}^{T_C} \left(c_{pg}(T) \cdot w(T) \right) dT \tag{4}$$

$$Q_d = Q_{diz} + Q_{ddes} + Q_{dog} + Q_{dogg} \tag{5}$$

where:

Q_{diz} – heat from isosteric part of the process (curve A-B on Fig. 2)

Q_{ddes} – desorption of working fluid (curve B-C on Fig. 2)

Q_{dog} – heat required for heating the adsorbent from TB to TC (curve B-C on Fig. 2)
Q_{dogg} – heat required for heating the adsorbate from TB to TC (curve B-C on Fig. 2)

Q_d – value of the heat supplied to the absorber 1 in the transition from state A to state C.

3.2. Heat balance of the condenser

$$Q_{sskr} = m_{ads} \left(w_{\min} - w_{\max} \right) r_{skr} \tag{6}$$

$$Q_{sob} = m_{ads} \int_{w_{\max}}^{w_{\min}} \int_{T(w)}^{T_{skr}} c_{pv}(T) dT dw \tag{7}$$

$$Q_s = Q_{sskr} + Q_{sob} \tag{8}$$

Gdzie:

Q_{sskr} – condensation of working fluid

Q_{sob} – reducing the temperature of vapor to a condensation

Q_s – heat rejected in the condenser

3.3. Heat balance of the evaporator

$$Q_p = m_{ads} \left(w_{\max} - w_{\min} \right) r_{par} \tag{9}$$

Where:

Q_p – heat received by the evaporator

3.4. Heat balance of adsorber no.2 (curve C-D-A on Fig. 2)

$$Q_{aiz} = m_{ads} \int_{T_C}^{T_D} \left(c_{pa}(T) + c_{pg}(T) w_{\min} \right) dT \tag{10}$$

$$Q_{aads} = m_{ads} \int_{w_{\min}}^{w_{\max}} \Delta H(w) dw \tag{11}$$

$$Q_{aob} = m_{ads} \int_{T_D}^{T_A} c_{pa}(T) dT \tag{12}$$

$$Q_{aobg} = m_{ads} \int_{T_D}^{T_A} \left(c_{pg}(T) \cdot w(T) \right) dT \tag{13}$$

$$Q_{ob} = m_{ads} \int_{w_{\min}}^{w_{\max}} \int_{T_{par}}^{T(w)} c_{pv}(T) dT dw \tag{14}$$

$$Q_a = Q_{ads} + Q_{aads} + Q_{aob} + Q_{aobg} + Q_{ab} \tag{15}$$

Where:

Q_{aiz} – heat from isosteric part of the process (curve C-D on Fig. 2)

Q_{aads} – absorption of working fluid (curve D-A on Fig. 2);

Q_{aob} – heat rejected while lowering the temperature of the adsorbent (curve D-A on Fig. 2);

Q_{aobg} – heat rejected while lowering the temperature of the adsorbate (curve D-A on Fig. 2)

Q_{ob} – heat used to change temperature f the gas from evaporation temperature to adsorption temperature (curve D-A on Fig. 2)

Q_a – heat rejected from absorber no 2 during the transition from the state C to state A.

4. Adsorbent-adsorbate sets

Proper operation of the absorption cooling apparatus depends primarily on the adsorbate-adsorbent sets used. Well-designed and efficient cooling unit should have a large adsorption capacity and its large temperatures change. Adsorbent should have the ability to adsorb large quantities of the adsorbate at low temperatures, and to the effective desorption by an increase in temperature. Its properties should not change in time and repeated use. Adsorbate should have low evaporation temperature and low saturation pressure (1-5 atm) in a normal operating temperature, high evaporation heat, small size particles, chemical stability, non-flammability, non-toxicity and corrosivity. The choice of a set of adsorbate-adsorbate affect the cost and availability in the market. The most common systems are: active carbon-methanol, active carbon fibers-methanol, activated carbon-ammonia, water-zeolites, silica gel-water, calcium chloride-ammonia, adsorbents composite – ammonia [2].

5. Prospects for the development and conclusions

In the shipbuilding industry we are dealing with significant amounts of waste heat, you may reflect on use of plant waste heat driven eg. cooling water main engine. The advantages of adsorption refrigeration include simplicity of design with no moving parts, shock resistance, quiet operation, no problems with corrosion. no dangerous gases or materials, no dangerous pressures, very low power consumption (circulating pumps only), automatic operation by very simple units (no computer needed) pro eco operation improves energy balance of the ship. Cold water can be used for cooling accommodation rooms, server rooms, kitchens, fridge rooms, and cargo.

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