Exergy and environmental analysis of the one stage vapor compression marine refrigerating machine working with ammonia

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Abstract: - Marine refrigerating equipment is used for shipboard refrigeration of products as well as for air conditioning. Marine refrigeration is also used for maintaining cargo products in liquid form that would otherwise evaporate when stored at ambient conditions.

The exergy analysis presented in this paper will allow specialists to improve the design and operation of one stage vapor compression refrigerating machines on board the ships. The chosen refrigerant is ammonia due to its excellent thermodynamic properties and friendly environmental behavior.

Key-Words: - marine refrigeration, exergy analysis, ammonia.

1 Introduction

Due to the fact the world population will met about 9 billion inhabitants in 2050, the food transport demand will increase in the next years.

World marine refrigeration is beset with three problems at present:

- high energy consumption – energy consumption on fishing vessels increased substantially during the last two decades because of the oversized thermal systems (leading to poor overall energy efficiency) and of the varying load on the systems during fishing;
- space requirement of equipment – having in view the stability on seas, it is difficult for the refrigeration equipment to work with security and stability; some refrigeration equipment occupies large spaces on board the ship because of their volume leading to the affecting of the loading quantity of ships;
- the environmental issue – the common refrigerants that have been used for years in marine refrigeration, known as CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons), are still being phased out because they contain chlorine, which depletes Earth's stratospheric layer; replacement for these refrigerants are known as HFCs (hydrofluorocarbons), which contain fluorine instead of chlorine (so are non-ozone-depleting); for some systems the cargo itself is used as refrigerant (when caring ammonia, propane or butane); the environmental concern has brought ammonia back into attention after many years, Lloyd's Register publishing new guidance notes covering the use of ammonia as a marine refrigerant (like: ammonia should only be used in indirect refrigeration systems, with the use of a secondary heat exchange fluid).

2 Exergetic analysis of the one stage compression refrigerating machine

The exergetic analysis indicates the path to follow for structural improvement due to the fact that it is used to develop, assess and improve energy conversion systems.

The one stage compression refrigeration machine and the representation of the cycle in the T-s diagram are presented in Figure 1. The flow chart of the machine contains a compressor (CM), condenser (CD), throttling valve (TV) and evaporator (EV).

The "product" of a refrigerating machine is the heat removed from the cooled space, while the "fuel" is the mechanical work consumed by the refrigerating compressor. A study based on the exergy analysis allows the assessment of the quantity and quality of the refrigeration.

The exergetic balance for the discussed cycle is written as:

$$\sum \dot{E}_Q = \sum \dot{W} + \sum \dot{E}_D \qquad (1)$$

Where the exergy rate ($\dot{E}_Q$), the power input ($\dot{W}$) and the exergy destruction ($\dot{E}_D$) are measured in Watts.

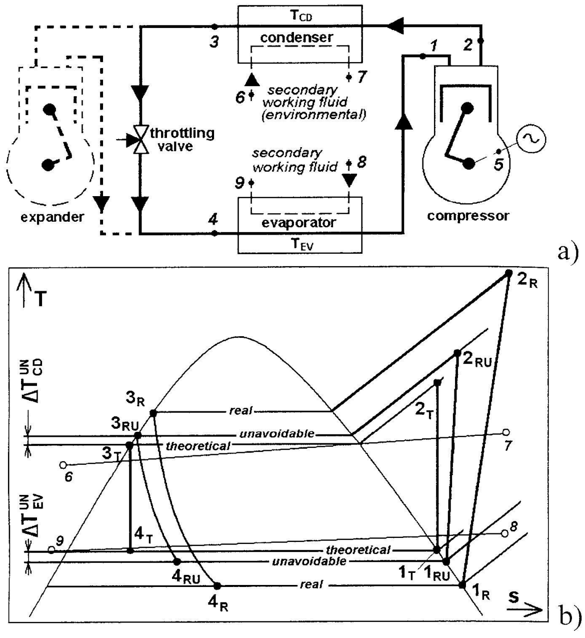

Fig. 1 Simple refrigeration machine: schematic and T-s diagram.

Having in view that every technological system has a productive function and consumes specific resources, the exergetic balance equation becames:

$$\dot{E}_F = \dot{E}_P + \sum \dot{E}_D \tag{2}$$

where $\dot{E}_F$ and $\dot{E}_P$ represent the exergy rate of fuel (consumed resources) and product (useful task), in Watts.

The exergetic efficiency, calculated to evaluate the performance of a system, is given by the ratio between the product rate and the fuel rate:

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\sum \dot{E}_D}{\dot{E}_F} \tag{3}$$

In order to assess the exergy destruction in every component of an energy conversion system, the exergy destruction in the k-th component is splitted in two parts: endogenous ($\dot{E}_{D,K}^{EN}$) and exogenous ($\dot{E}_{D,K}^{EX}$) [Morosuk and Tsatsaroniis, 2008].

The endogenous part of the exergy destruction in the k-th component refers to the irreversibilities taking place in the focused component when it operates at its current efficiency and the other components work in an ideal way. The exogenous part of exergy destruction in the k-th component is associated with irreversibilities taking place in the rest of the components.

So:

$$\dot{E}_{D,K} = \dot{E}_{D,K}^{EN} + \dot{E}_{D,K}^{EX} \tag{4}$$

Also, the exergy destruction in the k-th component might be splitted into unavoidable and avoidable, in order to measure the improvement capacity of the thermodynamic efficiency of a component. Thus, the unavoidable part of exergy destruction in the k-th component ($\dot{E}_{D,K}^{UN}$) is the part of the exergy destruction that cannot be eliminated even if the best available technology is used. The avoidable part of the exergy destruction in the k-th component ($\dot{E}_{D,K}^{AV}$) is the remaing part, being given by the difference between total and unavoidable exergy destruction and indicating the mean of improving the considered component of the system.
So:

$$\dot{E}_{D,K} = \dot{E}_{D,K}^{UN} + \dot{E}_{D,K}^{AV} \tag{5}$$

If the two options of splitting the exergy destruction in the k-th component are combined, results that:

$$\dot{E}_{D,K} = \dot{E}_{D,K}^{UN,EN} + \dot{E}_{D,K}^{UN,EX} + \dot{E}_{D,K}^{AV,EN} + \dot{E}_{D,K}^{AV,EX} \tag{6}$$

The avoidable endogenous and avoidable exogenous parts of exergy destruction in the k-th component are parts of the exergy destruction that can be reduced. Thus, $\dot{E}_{D,K}^{AV,EN}$ can be diminished by improving the focused component, while $\dot{E}_{D,K}^{AV,EX}$ can be diminished by improving the rest of the components or the subsystem structure.

3 Theoretical, real and unavoidable cycles

If the type, quantity and quality of a product are depending on the parameters of its physical environment, the exergetic performance of the considered system increases at the reduction in fuel consumption or exergy destruction. For the subsystems interacting with the external medium the surrounding will be selected to cross the environment so that all exergy destructions become exergy losses.

Exergy destructions are calculated as:

$$\dot{E}_{D,CM} = \dot{W}_{CM} - \left(\dot{E}_2 - \dot{E}_1\right) \quad (7)$$

$$\dot{E}_{D,CD} = \left(\dot{E}_2 - \dot{E}_3\right) - \left(\dot{E}_7 - \dot{E}_6\right) \quad (8)$$

$$\dot{E}_{D,CV} = \left(\dot{E}_4 - \dot{E}_1\right) - \left(\dot{E}_9 - \dot{E}_8\right) \quad (9)$$

$$\dot{E}_{D,TV} = \left(\dot{E}_3^M - \dot{E}_4^M\right) - \left(\dot{E}_4^T - \dot{E}_3^T\right) \quad (10)$$

In the above equation superscripts “M” and “T” refer the mechanical and thermal part of the physical exergy.

In figure 1 can be seen the theoretical cycle ($1_T - 2_T - 3_T - 4_T$), the real cycle ($1_R - 2_R - 3_R - 4_R$) and the cycle with unavoidable exergy destructions ($1_{RU} - 2_{RU} - 3_{RU} - 4_{RU}$) of the refrigeration machine.

The operating conditions are: refrigerant: ammonia (R 717), $\dot{Q}_{cold} = 100\ kW$, shell-and-tube condenser cooled by water with $T_6 = 20^\circ C$ and $T_7 = 25^\circ C$, the secondary working fluid for the evaporator is the air with $T_8 = -5^\circ C$ and $T_9 = -15^\circ C$.

The parameters specific to the theoretical cycle are: $T_{CD}^T = 23{,}8^\circ C$; $\Delta T_{CD}^T = 0^\circ C$; $\eta_{CM}^T = 1$; $\eta_{ex}^T = 1$ (in this cycle is used an isentropic expander, not a throttling valve); $\Delta T_{EV}^T = 0^\circ C$; $T_{EV}^T = -15^\circ C$; $\dot{E}_{D,K}^T = 0$ for each component.

The parameters assumed for the real cycle are: $T_C^R = 30^\circ C$; $\Delta T_{CD}^R = 6{,}2^\circ C$; the isentropic efficiency of the compressor $\eta_{CM}^R = 0{,}8\ (< 1)$; is considered the throttling process; $\Delta T_{EV}^R = 10^\circ C$.

Thermodynamic data for the real cycle of the refrigerating machine for the refrigerant, water and air are given in Table 1 [Morosuk and Tsatsaronis, 2007].

Table 1 Thermodynamic data for the real cycle of the refrigerating machine

working fluid	stream	T [°C]	p [bar	h [kJ/kg]	s [kJ/kg]	e^{Ph} [kJ/(kg·K)]
Refrigerant $g=0{,}1$ kg/s	1	-25	1,51	1430	5,98	67,5
	2	153	11,6	1810	6,17	393,2
	3	30	11,6	341,6	1,49	296,1
	4	-25	1,51	341,6	1,59	246,9
	0	20	1	1536	6,57	0
water $g=6{,}45$ kg/s	6	20	1	83,93	0,3	0
	7	25	1	104,8	0,37	0,18
	0	20	1	83,93	0,3	0
air $g=9{,}94$ kg/s	8	-5	1	268,3	6,76	1,14
	9	-15	1	258,2	6,72	2,29
	0	-20	1	293,4	6,85	0

By adding to the theoretical cycle irreversibilities caused by ΔT_{CD}^{UN}, ΔT_{EV}^{UN}, $\eta_{CM}^{UN} < 1$ and the throttling process, is obtained the cycle with unavoidable exergy destructions. Parameters of this cycle are: $\Delta T_{CD}^{UN} = 0{,}2^\circ C$; $\eta_{CM}^{UN} = 0{,}95\ (< 1)$; is considered the throttling process; $\Delta T_{EV}^{UN} = 0{,}5^\circ C$.

Values of unavoidable exergy destructions in the components of the refrigerating machine are given in Table 2.

Table 2 Results of the exergetic analysis

Component	$\dot{E}_{F,K}^R$ [kW]	$\dot{E}_{P,K}^R$ [kW]	$\dot{E}_{D,K}^R$ [kW]	$\dot{E}_{D,K}^{UN}$ [kW]
CM	35	30	5	0,8
CD	9	1	8	2,16
TV	22	19	3	1,5
EV	18	11	7	2,45

4 The need of ammonia use in marine refrigeration

Environmental challenges are becoming nevralgic issues and need to be analyzed. Climate change is directly connected with the concentrations of greenhouse gases in the atmosphere and with increased average temperatures. As a results of the concern, was signed, in 1997, the Kyoto Protocol. The worldwide regulations have been imposed in order to phase-out the production and consumption of CFCs and HCFCs for the protection of the stratospheric ozone layer. Looking for alternatives presenting low Global Warming Potential and reduced likelihood of other environmental impacts, natural refrigerants, like ammonia, are gaining important places on the market of alternative refrigerants.

Ammonia has been increasingly used in marine refrigeration equipment. Thus, ammonia is meet on reefer ships, as refrigerant for sorption ice machine, but also on fishing vessels as single refrigerant or in combination with CO_2, especially for low temperatures.

Ammonia is a natural medium-temperature refrigerant, having very good environmental and thermodynamic properties:

1) Ammonia is a green refrigerant: ODP=0 and GWP=0;

2) Ammonia has critical temperature and critical pressure of 132,3°C and 11,33 MPa, higher than that of R 22 (92,6°C and 4,99 MPa) or R 410 A (70,2°C and 4,79 MPa). Ammonia has a low standard boiling temperature (-33,4°C), a large volumetric refrigerating capacity, a high conductivity coefficient, a higher evaporative latent heat compare with the one of R 22 (6,4 times) or R 410A (5,5 times) at –15°C, a low throttling loss and a high refrigeration coefficient. Are found smaller size compressors and heat exchangers when using ammonia, compared with R 22, for the same temperature and refrigerating capacity.

3) The molecular weight of ammonia is 17 and his vapor density is lower than air; in case of leakage, ammonia rises and escapes easily; also it easily dissolves in water while a large leakage occurs.

4) Ammonia is cheaper than R 22, for the same volume.

But ammonia is far of being an impeccably refrigerant. His disadvantages being:

1) A high adiabatic coefficient and high compressor discharge temperature at low evaporating temperature and high condensing temperature. It is imposed the cooling to assure the function of the lubricating oils.

2) Ammonia corrodes zinc, copper and copper alloys, being needed materials like steel or aluminium.

3) Ammonia causes health troubles to persons exposed to concentrations over the limit, and causes explosion with flame for a concentration in air of 16–25% at high temperature.

5 Discussion and results

The exergy analysis for the real cycle of the one stage vapor compression refrigerating machine working ammonia revealed that the highest value of exergy destruction is obtained for the condensation process, while the highest value of the unavoidable exergy destruction is found for the evaporation process, not for the condensation $\dot{E}^{R}_{D,CD} = 8\ \text{kW};\ \dot{E}^{R}_{D,EV} = 7\ \text{kW}$. So, remembering the definition of the unavoidable exergy destruction, the improvement of the system should be oriented towards the condensation process ($\dot{E}^{UN}_{D,CD} = 2{,}16\ \text{kW};\ \dot{E}^{UN}_{D,EV} = 45\ \text{kW}$).

Ammonia has ODP and GWP equal to zero. It presents high refrigeration system energy performance, excellent thermodynamic properties and high heat transfer coefficients. Ammonia vapors are lighter than air. It might be easily detected by smell or by a variety of electromechanical and electronic sensors. Ammonia is cheap and available on the market.

6 Conclusion

The exergy analysis indicates the direction to be followed for a structural improvement. The analysis developed only on the First Principle of Thermodynamics is not able to reveal malfunctions occurring in the studied system.

The exergy analysis depicted in this paper offered information related with the location of internal malfunctions in one stage refrigerating machines, working with ammonia as a refrigerant. Having in view the spread of this kind of technology in marine refrigeration, it is important to find out that the improvement of the system must be started with the condensation.

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