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Efficiency analysis of alternative refrigerants for ejector cooling cycles

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ABSTRACT

Computer software, basing on the theoretical model of Huang et al. with thermodynamic properties of selected refrigerants, was prepared. Investigation was focused on alternative refrigerants that belong to two groups of substances: common solvents (acetone, benzene, cyclopentane, cyclohexane and toluene) and non-flammable synthetic refrigerants applied in Organic Rankine Cycle (ORC) (R236ea, R236fa, R245ca, R245fa, R365mfc and RC318). Refrigerants were selected to detect a possibility to use them in ejector cooling system powered by a high-temperature heat source. A series of calculations were carried out for the generator temperature between 70 and 200 °C, with assumed temperatures of evaporation 10 °C and condensation 40 °C.

Investigation revealed that there is no single refrigerant that ensures efficient operation of the system in the investigated temperature range of primary vapor. Each substance has its own maximum entrainment ratio and *COP* at its individual temperature of the optimum. The use of non-flammable synthetic refrigerants allows obtaining higher *COP* in the low primary vapor temperature range. R236fa was the most beneficial among the non-flammable synthetic refrigerants tested. The use of organic solvents can be justified only for high values of motive steam temperature. Among the solvents, the highest values of entrainment ratio and *COP* throughout the range of motive temperature were noted for cyclopentane. Toluene was found to be an unattractive refrigerant from the ejector cooling point of view.

1. Introduction

Conventional air conditioning systems powered by electricity are widely used in large agglomerations. Using them, however, results in high maintenance costs and, above all, the increased emission of harmful gases. Hence, it is extremely important to develop new solutions in the refrigeration area that will ensure the improvement of environmental conditions.

An attractive solution is an ejector system (Fig. 1) driven by thermal energy (e.g. obtained from solar collectors), which does not have a compressor to force a working cycle. The heart of this system is the ejector consisting of a four parts: motive nozzle, suction nozzle, mixing chamber, and diffuser.

An unquestionable advantage of this solution is the lack of movable parts in the device, the ability to work with environmentally friendly refrigerants, working devoid of vibration and noise, and low investment costs.

Unfortunately, due to low coefficient of performance (*COP*), these devices are not widely used in the market of refrigeration and air conditioning. However, much research is conducted to optimize and improve these systems, mostly in the field of ejector design, improvement of computational models, or combining them with compressor or absorption systems.

2. Refrigerant selection

High efficiency of the energy conversion in ejector system depends on a type of refrigerant. The ideal refrigerant should fulfill a number of assumptions regarding the thermodynamic properties, safety and environmental aspects, among others:

- Wide operating temperature range—higher motive steam temperature results in higher entrainment ratio and a higher value of *COP*.
- High latent heat of vaporization in evaporation and generation temperature to minimize the circulation rate per cooling unit.
- Good cooperation with a condensate pump—working medium cannot cause cavitation, as an increase of power consumption of the pump will result in a low efficiency of the system.
- No impact on the environment (zero ODP, low GWP) and safety in contact with people and cooled products.
- Availability and low cost.

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Nomenclature

A	area (m^2)
c_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
C_r	compression ratio
COP	coefficient of performance (=Q_e/Q_g)
GWP	global warming potential
h	specific enthalpy ($kJ\,kg^{-1}$)
NBP	normal boiling point
ODP	ozone depletion potential
P	pressure (kPa)
Q	heat rejected or supplied (W)
OEL	occupational exposure limits (ppm v/v)
T	temperature (°C)

Greek symbols

γ	heat capacity ratio
η	efficiency
ω	entrainment ratio

Subscripts

1 … 3	points of ejector and cycle analysis
b	end of mixing section
c	condenser
crit	critical point
d	diffuser
e	evaporator
g	generator
m	mixing
s	secondary or shock
t	throat
th	thermal
y	location of choking for the entrained flow

It is obvious, however, that the ideal refrigerant does not exist, and the choice of the optimal working fluid requires a compromise in the above assumptions. The proper choice of a working fluid, which optimally matches discussed ejector cycle, allows for achieving high performance at low system charge and low refrigerant cost.

The aim of this paper is to present a possibility of using selected non-flammable refrigerants and common solvents as working fluids in ejector refrigeration system. Synthetic refrigerants considered in this article are currently being used and therefore their description is presented briefly. More attention was paid to the properties of organic solvents as new substances potentially attractive to use in refrigeration.

2.1. Non-flammable refrigerants

Since a revelation about the harmful impact of chlorofluorocarbon (CFC) refrigerants on the environment, many alternative fluids with zero ODP have been proposed. Refrigerants R236ea and R245ca have been suggested for application in high temperature heat pumps. However, due to a high normal boiling temperature, these refrigerants were not suitable for operation in systems with low-temperature evaporation. Recently, R236ea/fa and R245ca/fa as well as R365mfc are mainly used as working fluids at low temperature ORC systems for low grade waste heat recovery [1–5].

2.2. Common organic solvents

Considered solvents were described in details, based on [6].

Acetone (CAS No. 67-64-1) is a substance with a sweet taste and a characteristic odour of decaying apples. It occurs naturally in plants and volcanic gases. It is also a component of car exhaust and tobacco smoke. The use of acetone in industry is primarily based on its miscibility in water, alcohols, and most oils. It is used as a solvent for paints and varnishes and in the manufacture of plastics and chemicals. It is a commonly used ingredient in detergents and cosmetics. Acetone evaporates quickly, whether liquid or solid. It irritates eyes and respiratory system. Inhaling moderate levels of acetone can cause headaches, nausea, and the increase in rate of heart beat. In addition, acetone is highly flammable and its vapors are explosive. The Committee on Toxicology of the U.S. National Research Council's recommends 1000 and 200 ppm 24 h emergency exposure limit and 90 day continuous exposure limit for acetone, respectively. With regard to refrigeration, so far acetone was used in adsorption [7] and absorption units [8] (as a pure refrigerant or a mixture's component) and chemical heat pumps [9].

Benzene (CAS No. 71-43-2) is one of the major chemical substances in the world and is used to produce other chemicals, mainly styrene and cyclohexane. Benzene is widely distributed in the environment and its major sources are combustion gases,

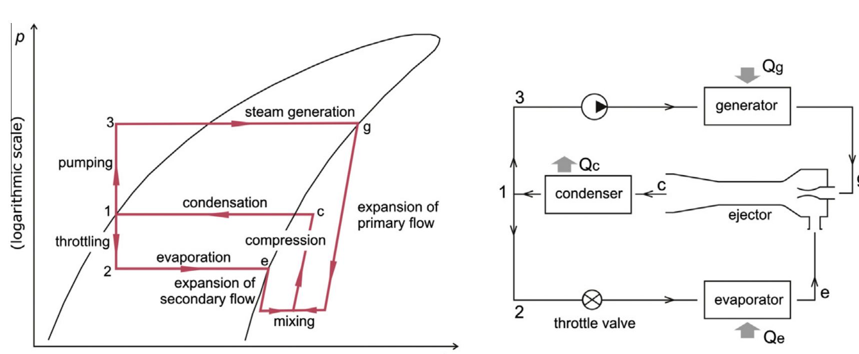

Fig. 1. Ejector cycle in p–h graph and configuration diagram of ejector refrigeration system.