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Experimental investigations of solar driven ejector air-conditioning system

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ABSTRACT

Recently, a rapid growth in various applications of ejector refrigeration systems has been observed in numerous sectors. With the applications based on solar or waste energy, designed to supply the motive energy have becoming widespread, a real alternative to compression devices in air-conditioning technologies has become a fact. Furthermore, it has been shown that ejector systems may effectively compete with absorption systems under temperature of the motive heat source lower than 80 °C. This paper presents experimental investigations carried out on a specially constructed prototype/stand for the ejector air-conditioning, operating with isobutane as a working fluid under motive vapour temperature below 75 °C. The effects of operation parameters have been thoroughly analysed. The ejector cycle performance coefficient was presented and discussed. The loss coefficient for the ejector was determined as well. It has been shown that loss coefficient in the investigated set-up is higher than 0.75.
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1. Introduction

Individual residential air-conditioning worldwide consumes over 11% of electric energy used for household purposes. For buildings with applied central air-conditioning systems it comprises a substantially larger share, even one-third of total electric energy consumption [1]. Many sources show a significant increase in the use of air conditioning, especially in southern countries, creating serious supply difficulties during peak load periods. Moreover, predictions indicate a massive growth in energy consumption and air-conditioned area in the EU during the next 15 years, increasing approximately in 50% [2]. Air-conditioning creates two sources of environmental pollution: (1) direct emission of greenhouse gases, especially for working fluids belonging to HFC group, and (2) emission of the greenhouse gases during generation of electric power to drive the system. Both sources are contributing significantly to the global warming effect. Additionally, with energy cost rising constantly, industry is looking for reduction of electric energy expenses as a means of lowering their fixed costs in order to stay competitive.

This paper presents development in air-conditioning technology that reduces greenhouse gases emission with the use of natural refrigerants which subsequently results in the reduction of the electric power consumption. Here, free or inexpensive low-temperature heat source – either solar or waste heat is effectively used as an alternative to conventional electricity. This solution has another important advantage, namely, direct correlation between motive power and the heat flux which need to be removed from the cooled room.

A solar-powered ejector air-conditioning system was introduced in 1993 by Sokolov and Hershgal, as a way to harness solar renewable energy for the purposes of air-conditioning [3]. The use of sustainable solar energy as the main heat input for cooling systems has led to several studies on available ejector A/C systems. The most comprehensive state-of-the-art study on solar air-conditioners is presented by Abdulateef [4]. He admits that, although many research groups worldwide have performed theoretical calculations, followed by computer simulation and experimental work, still no commercial solar system has been designed to-date. Several simulation models and experimental studies are found in literatures [5–15] for various working fluids, including R123 [5], steam [6,9–11], R141b [12], R134a [7,13,14], and ammonia [15]. Eleven refrigerants for ejector refrigeration system, including water and halocarbon compounds (CFCs, HCFCs and HFCs) have been tested by Sun [16], while Selvaraju and Mani [17] investigated only environmentally friendly refrigerants. However, one of the first researchers who mentioned the possibility of using natural refrigerants in solar-driven systems is Pridasawas [18]. He conducted a theoretical analysis for isobutane

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Nomenclature

A	area (m^2)
COP	coefficient of performance
h	specific enthalpy (kJ kg^{-1})
K	loss coefficient, Eq. (2)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (MPa)
P	mechanical power (W)
$\dot{Q}$	heat flux (W)
t	temperature (°C)
ΔT	subcooling/superheating of liquid/vapour (K)
U	mass entrainment ratio, $U = \dot{m}_e/\dot{m}_g$

Greek symbols

φ	velocity coefficient

Subscripts

1,2, 3, 4,...	thermodynamic state of refrigerant
c	condenser
d	diffuser
e	evaporator; secondary fluid
g	generator; primary fluid
h	heating fluid
i	inlet
m	mixing chamber
n	nozzle
o	nozzle outlet
p	mechanical pump
s	saturation; isentropic process
th	throat
*	critical

and concluded that it had the potential to perform well in ejector systems due to its small vapour volume, not requiring large ejector dimensions. It should be noted that choice of the working fluid for solar air-conditioning systems is extremely significant because of the strong influence of the thermodynamic fluid properties on the system efficiency. Moreover, the working fluid should fulfil environmental criteria such as zero ODP (ozone depletion potential) and as low GWP (greenhouse warming potential) as possible. Therefore the natural fluids are thought to be the best option. The energy efficiency of the system was theoretically analysed by Butrymowicz et al. [19] for the following fluids: isobutane, ammonia, propane, methanol, water. It was shown in the paper that the system operating with isobutane gives the highest energy efficiency. Later, Butrymowicz et al. [20] presented the first experimental results of the ejector refrigeration system operating with isobutane driven by low-temperature heat source. On the basis of these results in this paper the loss coefficient K of the ejector refrigeration cycle is determined. From a practical point of view, the loss coefficient is being considered as a crucial factor in the engineering calculations and design of the solar ejector air-conditioning systems. The ejector design process requires a priori prediction of the entrainment ratio. For given operating parameters the theoretical mass entrainment ratio can be predicted using simple calculation model, e.g. Paliwoda [23]. However, prediction of the actual values of the mass entrainment ratio requires more sophisticated models which are in most cases based on gas dynamic functions prepared for perfect gases, e.g. Huang et al. [26]. In addition, the isentropic efficiencies of the ejector components need to be known. To the best of our knowledge, these parameters for the system operating with isobutane have never been investigated and published. On the other hand, the time-consuming CFD techniques are also used for prediction of the entrainment ratio and ejector performance. In authors opinion the design of the ejector can be significantly facilitated. This can be accomplished using experimentally evaluated loss coefficient for the ejector combined with simple theoretical calculations. This combination is presented in the next section of the paper. It should be noted that all relevant literature provides no information about the loss coefficient of the ejector cycles operating with hydrocarbons. Also, the information on the loss coefficient of the ejector could be the first step in possible further improvements of the ejector efficiency, especially under low temperature driven refrigeration ejector system.

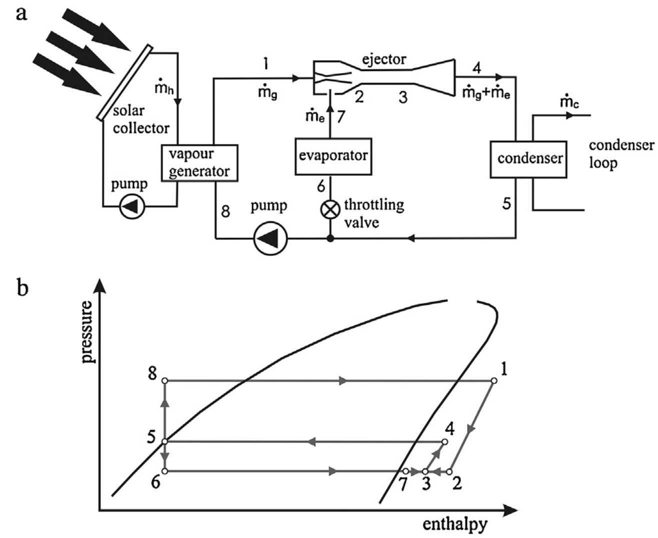

Fig. 1. (a) Schematic of the ejector refrigeration system. (b) Thermodynamic cycle of the ejector refrigeration system for isobutane.

2. Ejector refrigeration system

Ejector refrigeration system (Fig. 1) is a modification of a well-known vapour compression cycle. Instead of pressurizing the refrigerant by a mechanical compressor, an ejector compresses refrigerant vapour flowing from the evaporator and discharges it to the condenser. The motive vapour is generated in the vapour generator which is heated by low-temperature heat source.

Uses for thermal energy as the motive energy for ejector cycles make them comparable with absorption systems. In absorption systems the temperature of the heat source t_g in the majority of instances exceeds 100 °C. Although it is possible to find data showing the operation of the absorption systems under lower generator temperature, they have low value of COP. For frequently used single effect machines, the coefficient of performance falls within the range of 0.5–0.8, depending on operating parameters [21]. It is worth mentioning that a direct comparison of COP of the absorption system and ejector system may prove unreliable. There are four heat sources in absorption systems (evaporation, absorption, generation, condensation), whereas ejector systems require only three heat sources (evaporation, condensation and vapour generation). Comparison of $COPs$ of these systems can be made only if the same operating conditions are present. Even with the three parameters being identical (generation, condensation and evaporation temperature), the COP of the absorption system is likely to change with the change of the absorption temperature. Likewise, with temperature decrease t_g, the efficiency of absorption system also lowers, thus offsetting the difference between strong and weak solutions concentrations. It can be concluded that there is a minimum value of the motive temperature at which the absorption systems can

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