Energy Conversion and Management 150 (2017) 415–424

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Performances and compactness of a cooling system powered with PEMFC thermal effluent

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A R T I C L E I N F O

Keywords:
Refrigeration
Compactness
ORC cycle
Ejectors cycle
Energetic efficiency

A B S T R A C T

The thermodynamic study of a small scale cooling system combining an ORC cycle and a refrigeration cycle is carried out. The system includes the same components as those used for ejection cycles except that a combination of a vane compressor and a vane expander replaces the usual ejector. Real fluids properties, efficiencies of the pump, the compressor and the expender and pressure drops are considered. The isentropic efficiency of the expander was measured experimentally and the data were used in the thermodynamic model to simulate the complete system in steady state. The system is designed for operating with a 2 kW heating source at 65 °C corresponding to the heat rejected by a domestic PEMFC-type cell and a parametric study assess its performance, compactness and sensitivity when operating at off design. The evaporating temperature varies from −9.5 °C to +10.5 °C and the condensing temperature varies from 20.1 to 40.1 °C. Over the 12 fluids tested here, R1270 appears to be the most promising fluid, providing high performance, good compactness, low environmental nuisance and low off design sensitivity.

1. Introduction

Domestic PEMFC-CHP, or fuel cell cogeneration, is recognized by the International Energy Agency (IEA) as an efficient technology to reduce the global emissions of greenhouse gases, the primary energy consumption of housing and the risk of failure of the power grid during peaks demands. However, hot temperatures during summer days are not favorable to the effective use of rejected heat. Air conditioning systems correspond more to the needs of users during hot periods. Therefore, in order to not increase the consumption of electricity in summer, cooling system driven only by waste heat such as that produced by a domestic PEMFC appear as a promising alternative environmentally and friendly solution to conventional compression cooling systems. The two most widely used methods to produce cold from heat are absorption cycles and ejection cycles. These two technologies have been the subject of numerous studies and have reached very different levels of maturity. The absorption cycles are highly developed systems and require a sufficiently high temperature (typically 100 °C and more) to operate and are not nowadays suited to the thermal source of the current domestic PEMFC cells (typically 2 kW available at 65 °C). The ejector cycles are highly studied but very poorly developed, especially for small scale units. Injector systems can offer simplicity (no moving parts expected in the pump), reliability and low investment costs, but published studies show that the design of the ejector is challenging to obtain acceptable performances. Besagni et al. [1] present a comprehensive literature review on ejector studies. The authors investigate in the technology, the refrigerants, the cycles and the performances. The review put in advance that ejector cycles are compatible with thermal reject from PEMFC. Yan and Cai [2] investigates the ejector geometry parameters for a 2 kW air-cooled ejector cycle using R134a. The ejector performances largely depends on the operating conditions and the maximum measured entrainment ratio was approximately 0.35 and falls sharply when the system run out of nominal conditions. Eames et al. [3] test experimentally a 40 kW jet pump chiller using R245fa as working fluid. Their homemade ejector contains a movable primary nozzle and few geometries have been tested. The typical measured COP is around 0.15 when the evaporating temperature is 10 °C, the condensing temperature is 32 °C and the boiling temperature is 110 °C. Numerical simulations predict higher performances. Using the same test bench, Mazzelli and Milazzo [4] investigated the performance of a supersonic ejector. The system operated thanks a 90–100 °C low grade source. The predicted and measured entrainment ratio and COP are both closed to 0.4–0.6, corresponding to single effect absorption systems performance. Good agreement between predicted and measured data are obtained when ejector wall roughness is considered. Roman and Hernandez [5] used a model to predict the ejector cycle performance when using ecological fluids. The entrainment ratios vary from 0.3 to 0.9 when the evaporating temperature

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http://dx.doi.org/10.1016/j.enconman.2017.07.066
Received 29 May 2017; Received in revised form 3 July 2017; Accepted 30 July 2017
0196-8904/

Nomenclature

Symbols

d	diameter, (m)
H	enthalpy, (kJ kg^{-1})
$\dot{W}$	mechanical power, (kW)
$\dot{m}$	mass flow, (kg s^{-1})
T	Temperature, (K)
V	Velocity, (m s^{-1})
L	Length, (m)
α	dimensionless volume
β	entrainment ratio
δ	expansion ratio
τ	compression ratio
ρ	density, (kg m^{-3})
η	efficiency
Λ	friction coefficient

Subscripts

p	primary
eV	evaporator
gen	generator
s	secondary
reg	regenerator
ref	reference
cond	condenser
e	expender
is	isentropic
c	compressor
m	mechanical
i	point number
j	point number

goes from 5 to 15 °C. Chen et al. [6] present a review on ejector cycle principle, description and applications. Several combinations with other systems are presented. The authors clearly highlight the potentials of these systems and put forward the lack of knowledge to reliably design an ejector. Shestopalov et al. [7] study theoretically and experimentally the performances of a few kilowatts ejector cycle. Homemade ejectors cycle operates at off-design conditions and the entrainment ratio and COP are clearly dependent on the evaporating temperature and the condensing temperature. Recently, Galanis and Sorin [8] used 1-D thermodynamic model and perfect gas theory for determining the critical pressure ratio, the mixing efficiency and all the dimensions of an optimum ejector. Off-design performance for a fixed geometry ejector reproduces the experimental relations between the entrainment ratio, the compression ratio and the inlet conditions of the two fluids. Elbel and Lawrence present a recent review on transcritical ejection cycles using CO_2 [9]. The authors pointed out that the performance of ejector strongly depends on the efficiency of its components that depends highly from operating conditions. The assumption adopted in many models and considering constant yields under all conditions is not valid.

These previous studies point out that ejectors for small refrigeration systems are not mature and available technologies. All authors having published experimental results used homemade ejectors and studies show that entrainment ratios remain low and often lower than those predicted by simplified models. Also, it has been established that operating at off-design condition drastically decreases the ejector and the system performances. Authors have already proposed to combine an expander with a compressor [1,6,10–12]. The expander can replaces the pressure reducing valve to recovers the expansion energy of the liquid at the condenser output. This solution reduce irreversibilities losses usually located at the throttle valve and produces a compression of the fluid before entering the compressor, which reduces its consumption. Such improvement has also been tested for CO_2 transcritical fluids [13]. Wang et al. [10] combined a Rankine cycle with an ejector cycle to simultaneously produce cold and work. Vapor extracted during expansion in the turbine is used as motive fluid for the ejector. The working temperatures of components and the extraction ratio have a significant effect on power and refrigeration productions. Dai et al. [11] investigates the performances and exergy losses when introducing an expender between the generator and the ejector. Similarly, Habibzadeh et al. [12] presents the thermodynamic study of a thermal system which combines an organic Rankine cycle (ORC) and an ejector refrigeration cycle. The mechanical power produced at the expander is used to produce electricity. The optimum situation giving the smallest thermal conductance and exergy destruction is obtained for R601a. Hybrid ejector-compression studies [14,15] are also investigated to improve the coefficient of performance of the basic cooling machine. The ORC cycles are also the subject of numerous studies [16–31] including studies on fluids, technologies, energy and economic performance. Among these articles, some are interested with the nature of the fluids used for ORC applications. Wang et al. [17] used R245fa in a solar powered ORC. Marion et al. [18] test the performances of subcritical ORC cycles when R134a, R227ea and R365mfc are used as working fluid in small scale unit. Rayegan and Tao [19] compared the solar ORC performance of 117 organic fluids. Delgado-Torres [20] presented a theoretical study of solar ORC systems. The authors compared the predicted performances for twelve fluids, including hydrocarbons, hydrofluorocarbons and ammonia. Bara and Kim [21] found that R134a and R245fa are powerful in their ORC application. Quolin et al. [27] has shown that a scroll expander can also be used in ORC cycles. The engine cycle employing organic compounds (ORC) is nowadays an accepted technology for converting low-grade heat energy source into mechanical work [16]. Wang et al. [32] and Sun et al. [33] interest with combined ORC cycle's exergy efficiencies whereas Xu et al. [34] focused on the hydraulic pump efficiency impact. One can note that few studies deal with the small scale direct mechanical coupling of an ORC cycle with a refrigeration cycle.

2. Modeling of the cooling system

2.1. System description

Fig. 1 (case a) presents a description of the ejection cycle. The motive primary vapor produced in the generator flows through the convergent-divergent ejector nozzle (4). At the nozzle exit, the fluid accelerates up to supersonic velocity (5) and the pressure became very low. The flow enters in the mixing chamber entraining the secondary vapor flow from the evaporator (12). The two flows mixed in the mixing chamber (6) and decelerates in the diffuser section producing recompression process (7). The combined fluids flow through the preheater and then through the condenser (8) where phase change occurs. The condensate outgoing from the condenser (9) is split into two flows. The first one is directed to a pump (1), to the preheater (2) and returns to the vapor generator (3) to complete the Rankine cycle. The second one goes through the pressure reducing valve (10) and returns to the evaporator (11) to produce the useful cooling effect. In the present work, the potential energy present at the generator outlet (4) is converted into mechanical work using a vane expender, as shown in Fig. 1 (case b). The mechanical work recovered at the expander directly drives a vane compressor. This system contains therefore a conventional organic Rankine cycle and a conventional refrigeration cycle with a common condenser, as in ejector cycles. The main difference with the