Innovative solar and waste heat driven ejector air conditioners and chillers

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Abstract—This paper presents the research results of innovative solar and waste heat driven ejector air conditioners and chillers, which was carried out by the Odessa State Academy of Refrigeration, Ukraine, in cooperation with National Taiwan University, Taiwan. On the basis of obtained results, various advanced high-efficiency multipurpose ejector air conditioners and chillers are suggested for application in different areas.

Keywords—ejector; ejector cycle; ejector chiller; ejector air conditioner; solar energy; trigeneration; low-boiling refrigerant

I. INTRODUCTION

At the present time the majority of cooling systems are electrically driven compression chillers, which have a world market share of about 90%. To minimize emissions of pollutants and to reduce the primary energy consumption of air conditioners and chillers, thermal cooling systems offer interesting alternatives, especially if the low-grade heat from solar collectors or waste heat from cogeneration units can be used [1].

The thermal cooling technology based on ejector cooling machines (ECMs) can utilize solar and waste or exhaust heat, and operate with low-boiling environmentally friendly refrigerants.

Solar ECMs can produce cooling for air-conditioning, space-cooling and food storage in the range of evaporating temperatures from 12°C to −10°C. These systems can be driven by conventional single-glazed flat plate solar collectors with selective surface and vacuum tube solar collectors, which can be most economical for ECM by a proper choice of optimum generating temperature [2].

ECMs can also be powered by heat supplied from combined heat and power (CHP) systems. Cogeneration or CHP production is an old and well known technique for the rational use of energy. Combined heating, cooling and power (CHCP) production or trigeneration is however a quite recent technology and it is becoming an increasingly important energy saving option, particularly on small scale applications [3]. Various types of micro-trigeneration systems can be designed and developed using simple and reliable ejector chillers and air conditioners [4].

The main objective of this research is to study the advanced high-performance multipurpose ejector chillers and air conditioners driven by solar thermal energy and waste or exhaust heat. They are intended for commercial application under different climatic conditions in domestic and industrial cooling, refrigeration and air-conditioning systems, and which meet modern requirements of efficiency, reliability, and level of automation, as well as ecological and economical standards.

II. DESIGN OF SOLAR EJECTOR AIR CONDITIONERS AND CHILLERS

Solar-powered refrigeration for air-conditioning or space-cooling is very attractive, since cooling loads and the availability of solar radiation are generally in phase.

A solar ejector air conditioning system consists of a solar collector and a heat driven ECM. Solar collector converts solar radiation into thermal energy, which then is used to drive the ECM. The main feature of solar ECM is the solar collector and heating mode of the generator. Figs. 1-3 show the three different methods for heating the generator. Fig. 1 presents the design of solar ejector air conditioner (SEAC) with direct heating, that is the surface of the generator is the absorbing plate of the solar collector; Fig. 2 shows the design of SEAC with closed-loop mode for circulating heating medium in which heat is supplied by intermediate heat-transfer liquid – usually water, that is heated in solar collector. Fig. 3 shows the open-loop mode for heating water that first is used to cool the condenser to reduce the condensing temperature and raise the efficiency of ejector chiller [5].

The process of a continuously operating ECM is characterized by the points 1-9 illustrated in Fig. 4, which represents a diagram of an ejector cooling cycle with the following working principle. Refrigerant is heated and vaporized in the generator by solar thermal energy $Q_b$ at relatively high pressure $P_b$. This motive vapor, with a mass flow rate $\dot{m}_p$, flows through the primary nozzle of the ejector. At the exit of the nozzle, the accelerated flow becomes supersonic, which produces a low-pressure region in suction chamber of the ejector.

Hence, vapor, at low pressure $P_e$, with a flow rate of $\dot{m}_1$, is induced from the evaporator into the ejector. Primary and secondary fluids are mixed in the mixing section of the ejector and then undergo a pressure recovery process in the diffuser section. The combined stream flows to the condenser where it is condensed into liquid at intermediate pressure $P_c$. The heat of condensation $Q_c$ is rejected to the environment. Some of the condensate is returned to the solar-powered generator via an electrically driven feed pump,
consuming mechanical power \( W_{\text{mech}} \), whilst the remainder expands as it flows through an expansion valve before returning to the evaporator, where it re-evaporates to produce the necessary cooling effect \( Q_e \).

III. ANALYSIS OF EJECTOR DESIGN AND EJECTOR COOLING CYCLE PERFORMANCE

The supersonic ejector is the key component in the ejector refrigeration cycle. It is a simple jet device which is used in the ejector cycle for suction, compression, and discharge of the secondary vapor by force of the primary vapor.

Fig. 5 illustrates the structure of supersonic ejector with cylindrical mixing chamber. The ejector assembly can be divided into four main parts: a nozzle, a suction chamber, a mixing chamber, and a diffuser.

Operating conditions of an ejector are specified by operating pressures \( P_e, P_c, P_g \), expansion pressure ratio \( E = P_g/P_e \) and compression pressure ratio \( C = P_c/P_e \).

The performance of an ejector is measured by its entrainment ratio \( \omega \), which is defined as:

\[
\omega = \frac{m_e}{m_f}. \tag{1}
\]

Construction, geometry and surface condition of the supersonic ejector flow profile must provide the most effective utilization of primary flow energy for suction, compression, and discharge of the secondary vapor [5-9].

The performance of the ECM is usually measured by single coefficients of performance (COP), which is the ratio of the useful cooling effect \( Q_e \) produced in the evaporator over the gross energy input into the ejector cycle. But it should be taken into account that the ECM commonly utilizes a mechanical feed pump, and, consequently, an input of some amount of mechanical power \( W_{\text{mech}} \) in addition to a low-grade heat energy \( Q_g \).

However, in spite of the fact that the mechanical power \( W_{\text{mech}} \), consumed by the feed pump is very small compared to the thermal energy \( Q_g \) input to the generator to actuate ejector cycle, it may not be omitted [10]. Therefore, from both thermodynamic and economic points of view, the efficiency of the ECM cycle can be correctly characterized by using separately both thermal COP \( \text{COP}_{\text{therm}} \) and actual specific power consumption of mechanical feed pump \( W_{\text{mech}} \), which are defined respectively as:

\[
\text{COP}_{\text{therm}} = \frac{Q_e}{Q_g} = \frac{m_e q_e}{m_f q_g} = \omega \frac{q_e}{q_g} \tag{2}
\]

\[
W_{\text{mech}} = \frac{W_{\text{mech}}}{Q} = \frac{m_e \nu_g (P_g - P_c)}{\eta_{\text{pump}} m_f \nu_e} = \frac{\nu_g (P_g - P_c)}{\eta_{\text{pump}} \omega q_g} \tag{3}
\]

where \( \nu_g \) and \( \eta_{\text{pump}} \) are specific volume of intake refrigerant and feed pump efficiency, respectively; \( (P_g - P_c) \) is the generating and condensing pressure difference, kPa.

Analysis of (2) and (3) shows that the characteristics \( \text{COP}_{\text{therm}} \) and \( W_{\text{mech}} \) strongly depend on the operating
conditions, the efficiency of the ejector used and the thermodynamic properties of the refrigerant used.

![Ejector structure with cylindrical mixing chamber.](image)

Figure 5. Ejector structure with cylindrical mixing chamber.

Clearly, the operating efficiency of the ejector cycle and reliability of the ECM depend very much on the efficiency and the reliable performance of the feed pump, which is largely determined by the generator and condenser pressure difference \( P_g - P_c \). To decrease this pressure difference, and thus to increase the reliability of the system as a whole, it is preferably to use low-pressure refrigerants in the ejector refrigeration cycle.

The evaluation of performances of various refrigerants shows that the environmentally friendly low-pressure working fluids R600, R600a, R245fa and R245ca offer the best performance combinations and at present are the most suitable for application in ejector chillers, air conditioners and refrigerators [4,10].

IV. DESIGN OF AUTONOMOUS EJECTOR CHILLERS AND AIR CONDITIONERS

A conventional ECM usually requires an electrically driven feed pump which is the only component in the ejector cycle that has moving parts and therefore determines the reliability, leakproofness, and lifetime of the whole system. Utilization of thermally-driven feed pumps allows a cooling effect by using only heat energy. That makes the ECM independent from the source of electric power, i.e., autonomous [11].

Novel autonomous air conditioners and chillers using non-conventional hermetic thermo-gravity feeders are proposed and designed [11].

Fig. 6 shows a diagram of an autonomous heat driven split ejector system with two ejectors operating in parallel. This system is intended for simultaneous air conditioning and refrigeration.

Fig. 7 illustrates two different constructions of automatic float-type thermo-gravity feeders, which can be used in various small-capacity ejector chillers, air conditioners and refrigerators.

The operating principle of the proposed hermetic thermo-gravity feeders is as follows. A float-type feeder is located at the intermediate level between the condenser and generator and is connected to them by vapor and liquid lines. Gravity transports the primary fluid from the condenser to the generator via the feeder in two stages. The first stage is the filling of the feeder, and second stage is the evacuation of the liquid refrigerant from it. The process of automatic control is realized by a slide that opens and closes equalizing vapor lines in turns. The slide position depends on the liquid level in the feeder and is controlled by a float. Proposed thermo-gravity feeders are simple and reliable, and much less expensive than conventional mechanical feed pumps.

Instead of using a conventional electrically driven feed pump for ECM, using a thermally activated pump that converts thermal energy into mechanical energy to drive a mechanical feed pump is very attractive [11]. The application of such a heat-operated feed pump in the different ejector cycles provides an increase in both the reliability and the life expectancy of the whole system.

Fig. 8 shows a photograph of the experimental heat driven piston feed pump. The design of the thermo-pump is simple and reliable, and it is thought to be less expensive than a conventional electro-mechanical feed pump [11].
V. DESIGN OF TRIGENERATION SYSTEMS

In trigeneration systems, three kinds of prime movers can be generally used: reciprocating internal combustion engines (ICEs), combustion micro-turbines, and fuel cells, all three of which can be selected to match site conditions [4,5].

A diagram of a trigeneration system incorporating an ICE, an alternator, a heat recovery unit, and an ejector chiller is shown in Fig. 9. The basic components of the ejector chiller include an ejector, a generator, an evaporator, a condenser, an expansion valve, and a feed pump. The thermal energy of the exhaust gases is transferred through a heat recovery unit to a water circuit serving the generator of the chiller. The resulting cooling effect $Q_c$ can be used to provide air conditioning and space cooling to the local community or to improve the thermal efficiency of the engine cycle by cooling the intake air prior to ingestion to the engine cylinders. Thus, the main part of the exhaust heat can be recovered.

Fig. 10 illustrates the combination of a CHP system with low grade heat driven ECM that provides cooling of the ambient air before it enters the compressor that supplies high-pressure air to the micro-turbine combustion chamber. The introduction of the ejector cooling cycle does not require complex equipment, and such a technical solution provides both economic and environmental benefits [4].

VI. RESULTS OF INVESTIGATIONS OF VARIOUS EJECTOR REFRIGERATING MACHINES

Considerable developments and research into the area of low-grade heat driven ejector cooling and refrigeration technologies have been carried out at the Odessa State Academy of Refrigeration (OSAR) since 1950. On the basis of obtained results, scientific and technological fundamentals for the design, development, and manufacture of multipurpose ECMs have been developed [9,12,13].

About 20 experimental and preproduction models of the ECMs operating with refrigerants R11, R12, R134a, R141b, R142b, R236fa, R245fa and R600, driven by waste and exhaust heat and solar energy, have been designed, constructed, and tested in different climatic conditions over the last 35 years. Obtained experimental results have shown that COPs of ECMs operating with low-boiling refrigerants can be significantly increased by a proper selection of working fluid; by optimum design of the ejector construction and the ejector flow profile; by optimization of ejector cycle and operating conditions; by utilization of highly efficient heat exchangers; and via other approaches [4,7-15].

Recently several high-efficiency ECMs operating with refrigerants R141b and R245fa were developed, and COPs in the range of 0.5 – 0.7 were obtained at practical operating conditions. These results are very encouraging for air-conditioning and cooling applications because these COPs are similar to those for absorption cycle machines [6,7,8,14].

Thus, ECMs driven by solar energy and inexpensive low-grade waste and exhaust heat, could be suitable alternatives to water-LiBr absorption systems [5].

Fig. 11 presents the design and exterior views of various experimental supersonic ejectors tested with different low-boiling refrigerants. As it can be seen from the photos in Fig. 11, the majority of represented ejectors have two symmetrical suction inlets in order to provide axisymmetric equal distribution of the secondary flow in the suction chamber and thus to decrease the irreversibilities of gasdynamic processes, which occur in the ejector [5-9].

Various innovative multipurpose ejector air conditioners and chillers using environmentally friendly refrigerants R245fa, R245ca, R600 and R600a have been designed and developed recently at the Ejector Refrigeration Technology Center (Odessa, Ukraine). These ECMs are designed in packaged type with options: with water or air cooled condensers; with evaporators for air or liquid cooling; with direct or indirect-heated generators.

Figs. 12-13 illustrate the exterior views of various ejector chillers and air conditioners [5,15]. Their value-added features are as follows: simple and compact design; low capital investments and operating costs; minimal maintenance and repair expenses; all-around automation; no lubricant; no corrosive; small footprint and light weight; easy indoor/outdoor/rooftop siting; small cost of cooling output.

All engineered heat powered chillers and air conditioners with cooling capacities up to 10-15 kW are designed with thermo-gravity feeders and thermally driven feed pumps.
Unified plate heat exchangers, shell-tube, shell-coil, and other types of heat exchangers and components, all of which are serially produced by different refrigeration companies, are used in these machines. That ensures the high adaptability to existing refrigeration techniques and the low estimated production cost, which basically depends on the price of the heat exchangers used, which comprises about 30-60% of the total production cost. It should be noted that the manufacture of all proposed chillers and air conditioners substantially implies the fitter’s works.

Figure 11. Photographs of various experimental supersonic ejectors.

Figure 12. Compact water cooled ejector chillers with cooling capacities 100kW, 50kW, 30kW and 15kW.

In order to determine the fields of effective application of innovative ECMs, techno-economic comparison of various types of thermally powered cooling machines was carried out. It was estimated that the innovative multipurpose low-grade heat driven ejector chillers and air conditioners are suitable alternatives to water-LiBr absorption systems, especially when cooling capacities up to 100-200 kW are required [3,8,14].

ACKNOWLEDGMENT

This publication is based on the work supported by Award No.KUK-C1-014-12, made by King Abdullah University of Science and Technology (KAUST), Saudi Arabia.

REFERENCES


