“Solar Ejector Cooling System”
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Abstract

Interest in utilizing solar-driven refrigeration systems for air-conditioning or refrigeration purposes has grown continuously. Solar cooling is comprised of many attractive features and is one path towards a more sustainable energy system. Compared to solar heating, the cooling load, particularly for air-conditioning applications, is generally in phase with solar radiation.

The performance of solar cooling systems is strongly dependent on local conditions. Solar cooling systems can be efficiently operated in locations where sufficient solar radiation and good heat sink are available.
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1. Introduction

1.1 Ejectors History

Ejectors have been in use prior to 1900 where they found use in evacuating air from leaky low pressure steam condensers. An ejector in this application acts as a vacuum pump, driven by low pressure steam which was readily available in such environments. The ejector’s role was characterized by steady state conditions and empirical design. Efficiency was not as important as reliability.

Within 20 years, ejectors found widespread use as vacuum pumps in industrial settings. It was a small step to form a vapour compression heat pump using the ejector as a heat driven compressor. Steam driven ejector heat pumps became common in air conditioning, particularly of hotels and ships during the early 20th century; wherever there was a ready supply of low pressure steam or a steam boiler. Ejector systems were found to be low cost, very reliable and maintenance free.

During the 1930s, Freon refrigerants were developed and vapour compression heat pumps based on these new refrigerants were far superior in performance to ejector systems. Ejector air conditioning fell from favour for 50 years until the Montreal protocol of 1987 highlighted a link between Freon use and atmospheric ozone depletion.

This rekindled an interest in ejector technology and at about this time, two important improvements in ejector design were made. Firstly, refrigerants other than water were tested and found to perform better. Secondly, researchers began to look at system integration issues and to compose systems incorporating solar energy and hybrid designs.
The modern era of ejector research combines supersonic thermodynamics, computational fluid dynamics and experimental work. Despite this effort, the inner workings of the apparently simple ejector are not fully understood, but are reasonably well modeled.

Researchers are able to design ejectors with confidence and there are industrial ejectors ranging in size form several hundred watts to huge multi-megawatt steam ejectors.

1.2 What is a cooling system?

Apparatus used to keep the temperature of a structure or device from exceeding limits imposed by needs of safety and efficiency. In a mechanical transmission, the oil loses its lubricating capacity if overheated; in a hydraulic coupling or converter, the fluid leaks under the pressure created. In an electric motor, overheating causes deterioration of the insulation. In an overheated internal-combustion engine, the pistons may seize in the cylinders. The cooling agents customarily employed are air and a liquid (usually water), either alone or in combination. In some cases, direct contact with ambient air (free convection) may be sufficient, as in cooling towers; in other cases, it may be necessary to employ forced convection, created either by a fan or by the natural motion of the hot body. Cooling systems are used in automobiles, industrial plant machinery, nuclear reactors, and many other types of machinery.
1.3 Solar Cooling in Different Locations

Characteristics of the cooling demand are different at various locations. The performance of the whole system depends on both the cooling subsystem and solar converter efficiency. To provide cooling for one specific application, the right cooling cycle must be chosen in order to meet the desired cooling characteristics and temperature level. A suitable solar collector must also be selected in order to provide the right driving temperature for the chosen cycle. The dimension (size) of the solar collector strongly depends on the climate. An additional storage tank or auxiliary heater may be required to secure the cooling supply.

![Figure 1 Cooling Demand](image-url)
The cooling demand in tropical regions is generally higher than in locations to the north or south, but the required peak capacity may not much differ. Furthermore, the cooling load does not vary considerably in tropical regions over the course of the year for tropical regions. Therefore, the price of a cooling supply per kilowatt hour of cooling energy is lower for these locations. In some cities, such as Paris, the cooling demand in summer is quite high; therefore a system with a high cooling power is required in order to fulfill the desired cooling demand. The cooling load, however, lasts for a relatively short period of time, e.g. a few months at the most. Assuming that only the cooling demand is taken into account, the system might not be economically competitive to conventional cooling systems. On the other hand, the solar collector subsystem can provide heating in winter thus promoting project economy considerably.

![Figure 2 Maximum Cooling Power](image-url)
Figure 3 Required Solar Collector Area, Evacuated Tube

Figure 4 Required Solar Collector Area per 1 kW of Cooling Power in one year.
2. Solar Cooling Options and Technologies

The solar cooling system is generally comprised of three sub-systems: the solar energy conversion system, refrigeration system, and the cooling load. The appropriate cycle in each application depends on cooling demand, power, and the temperature levels of the refrigerated object, as well as the environment. A number of possible paths from solar energy to cooling services

Starting from the inflow of solar energy there are obviously two significant paths to follow, solar thermal collectors to heat or PV cells to electricity. For solar thermal collectors, different collector types produce different temperature levels. This indicates that the temperature level can be matched to various cycle demands.

The same type of temperature matching is important for the cold side of the solar cooling path, in the cold object. Since several cycles typically operates with water as a working fluid, it is impossible to achieve temperatures below 0°C for some cycles. The solar thermal-driven air-conditioning cycles can be based on absorption cycles, adsorption cycles, duplex rankine, desiccant cooling cycles, or ejector refrigeration cycles.

When using low temperature applications for food storage at 0 to -8°C, various cycles can be applied, the vapour compression cycle, thermoelectric cycle absorption cycle, adsorption cycle or a chemical reaction cycle. Applications requiring temperatures below 0°C generally require small storage volumes, freezing boxes. A suitable cycle for this application has proved to be the PV-driven vapour compression cycle, or a PV-driven Stirling cycle. The double effect absorption cycle, adsorption cycle and chemical reaction cycle can also be used, especially for larger storage volumes, ice production.
2.1 Description of a Ejector System

The ejector is a thermally driven compressor that operates in a heat pump refrigeration cycle. In a heat pump system, the ejector takes the place of the electrically driven compressor, but uses heat rather than electricity to produce the compression effect.

The ejector has no moving parts and is simple and reliable which make it attractive for commercial production. However, the thermal efficiency of the ejector is low which implies that the ejector requires a large solar collector and large condenser to operate in a heat pump application. Thus the savings in electricity consumption must be compared with the additional cost of the solar collector. One is trading capital cost for operating cost, as with most solar systems.

A liquid pump is required to generate a pressure difference for the ejector heat pump to operate, but since liquid is being compressed, the amount of electricity required is relatively small. All other components in the heat pump circuit are conventional.
The ejector cycle consists of high and low temperature sub cycles. In the high temperature sub cycle, heat that is transferred to the ejector cycle from the heat source causes vapourisation of the ejector cycle working fluid in the generator at a temperature slightly above the saturation temperature of the refrigerant. Vapour then flows to the ejector where it is accelerated through a converging-diverging nozzle.

2.3 Solar-Driven Ejector Refrigeration System

A solar thermal collector is used to supply heat to the generator as a major energy source for the ejector refrigeration subsystem, via a thermal storage and an auxiliary heater. An evaporator provides cooling to the conditioned space. In this case, the cooling load is assumed to be the already introduced small 150 m³ office building. Details of each subsystem are described in the following section, starting with the model of the solar collector subsystem, followed by the ejector refrigeration subsystem, and the cooling load.

Figure 6 A Solar Driven Ejector Refrigeration System
2.4 Solar Collector Subsystem

This subsystem consists of the solar collector, a storage tank, a pump, a controller and an auxiliary heater. Solar radiation is converted to heat by the solar collectors. The storage tank is used as thermal storage when solar radiation is not sufficient. The auxiliary heater is placed between the storage tank and generator of the refrigeration subsystem. If the temperature of the liquid coming from the storage tank is lower than the lowest generator temperature set point, the auxiliary heater will start.

The solar collector efficiency is defined as the ratio of the useful heat gain over any time period to the incident solar radiation over the same period. The instantaneous energy efficiency of the solar collector can also be expressed in the form of the average Bliss coefficient and the heat loss coefficient.
3. Ejector Refrigeration Cycle Subsystem

In the ejector, the primary vapour stream from the generator (a, Figure 8) accelerates through the nozzle of the ejector (b, Figure 8), creating a low pressure at the nozzle exit (c, Figure 8). This pressure is lower than the pressure in the evaporator (d, Figure 8), thus the vapour is drawn from the evaporator. In a mixing zone (e, Figure 8), at the end of the converging section, the two streams are mixed. After mixing, the combined stream becomes a transient supersonic stream. A transverse shock occurs along the constant area (f, Figure 8) and the diffuser sections (g, Figure 8) to balance the pressure difference. After the shock, the velocity of the combined stream becomes subsonic and is further reduced in the diffuser. The vapour from the ejector then goes to the condenser (h, Figure 8).
After the condenser, one part of the liquid working fluid is pumped to the generator and the rest goes to the evaporator, reaching the evaporation pressure by throttling in the expansion device.

The processes of the ejector refrigeration subsystem are represented in a pressure-enthalpy diagram in Figure 9. The model of the ejector refrigeration subsystem is based on the thermodynamic states in each operating point according to Figure 9 and the following equations. In the following nomenclatures in this section, the numbers in the subscription refer to the condition according to Figure 9 and,

- subscription ‘m’ refers to the condition in the mixing chamber of the ejector,
- subscription ‘g’ refers to the condition in the generator
- subscription ‘c’ refers to the condition in the condenser
- subscription ‘e’ refers to the condition in the evaporator
- subscription ‘is’ refers to the isentropic condition.
4. Ejector Design

Results from the energy analysis and dynamic simulation have demonstrated that a better understanding of the ejector is vital for the design of solar-driven ejector refrigeration systems. It is additionally the most complicated part to design in an ejector refrigeration cycle. The design of ejectors is typically based on the theoretical expression of ideal gas dynamics together with experimental data. Empirical equations for steam ejectors, on the other hand, are quite well known and can be found in several handbooks. Empirical design data for other working fluids, water, is however, rarely presented. The design procedure for each section is based on the theoretical expression of ideal gas behavior and some empirical equations found in literature.

![Ejector Geometry and Sections](image-url)
5. Conclusions

Solar energy as a renewable energy source for driving cooling machines has for a long time been a favorite topic for many researchers. In the early stages of development, solar cooling focused on refrigeration of perishable goods and vaccine storage. Today, the demand for air-conditioning for human thermal comfort is growing rapidly and occasionally influences the power supply structure in a negative manner. Solar cooling systems strongly depend on local conditions e.g. solar radiation, ambient temperature, or cooling load. Systems should therefore be specifically designed for each location, thereby obtaining the best performance. For thermally-driven systems, a solar cooling system requires less solar collector area per cooling demand (kWh) in tropical areas than in areas above the Tropic of Cancer or below the Tropical of Capricorn, provided that the building has a reasonable climate shell. One severe restriction for solar cooling in general and the ejector system in particular, is the heat rejection temperature. Heat sink temperatures must be kept as low as possible in order to maintain a stable operation and high performance. A good local heat sink such as a lake, a river or the sea or even a cooling tower can be used with additional parasitic energy consumption for the latter. The best solar cooling locations are therefore located near sufficient solar radiation and a good heat sink.
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