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A prescription for primary nozzle diameters for solar driven ejectors

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Abstract

There is a growing interest in ejector cooling systems driven by solar heat. One of the main problems with solar cooling using ejectors is that the ejector cannot operate well if the operating conditions stray from the design point temperatures. Ejectors with variable geometry have been proposed and modelling shows that they are able to increase the operating range of an ejector. In particular, ejectors with a variable primary nozzle throat diameter have been experimentally shown to enhance ejector performance.

This paper extends the work of others to provide a means to design a primary nozzle with variable throat diameter and variable nozzle exit diameter. The algorithm is extended to account for the behaviour of the solar collector and vapour generator. In this way, the nozzle diameters are determined as a function of the operating conditions ambient temperature and solar radiation. This correlation provides the basis for a practical nozzle control system.

Keywords: Ejector; Nozzle; Solar cooling; Variable geometry

1. Introduction

Space cooling using heat pumps is becoming increasingly popular particularly for residential applications. This is primarily due to the availability of low cost and high performance heat pumps. However, the proliferation of heat pumps is leading to difficulties in supply of electricity in some countries and high greenhouse gas emissions associated with both operating electricity and the refrigerant within the system. Solar driven cooling cycles using ejectors offer an alternative whereby the electricity consumption is largely reduced. Ejector technology has been used for over 100 years and has recently undergone a revival in interest for space conditioning applications.

The ejector is a thermally driven compressor that operates in a heat pump refrigeration cycle. In an ejector 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 cooling effect produced by a solar driven ejector is constrained by the solar collector area, the available solar radiation, the ambient temperature and the ejector's geometry.

The pressure required in the primary flow to the ejector nozzle increases with increasing condensing temperature. In order for the refrigerant to remain in a vapour state through the primary nozzle, its temperature must increase concurrently with its pressure. For solar driven ejectors, this implies that a solar collector will need to deliver higher temperature to the refrigerant in the vapour generator as the ambient temperature rises. Conversely, the ejector may relax its requirement for vapour generator temperature when condensing conditions are mild.

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Nomenclature

Symbols

A	area (m^2)
c_p	specific heat capacity at constant pressure ($\text{J kg}^{-1}\text{ K}^{-1}$)
d	diameter (m)
$F_R\,(\tau\alpha)$	collector optical efficiency
$F_R U_L$	collector heat loss term ($\text{W m}^{-2}\text{ K}^{-1}$)
G	solar radiation (W m^{-2})
h	enthalpy
$\dot{m}$	mass flow (kg s^{-1})
M	mach number
N_s	number of solar collector panels in series
p	pressure (Pa)
Q	power (W)
R	universal gas constant ($\text{J kg}^{-1}\text{ K}^{-1}$)
R_1, R_2	collector efficiency correction factors
T	temperature (K)

Subscripts

amb	ambient
c	collector
co	condenser
ev	evaporator
g	generator
i	inlet
mx	mixing chamber
o	outlet
p	primary flow
ne	primary nozzle exit plane
th	primary nozzle throat
s	secondary flow
t	test (flow rate)

Greek letters

γ	ratio of heat capacities
η	efficiency

Conceptually, the annual cooling yield of a solar driven ejector will be greatest when the solar collector is fully utilised. For a given solar collector power availability, the primary throat diameter would need to increase with decreasing vapour generator temperature. At high ambient temperatures, the required vapour generator temperature is also high and the nozzle throat diameter must decrease to limit its power consumption to match the solar collector power availability. Such a strategy would ensure that the available solar collector power is utilised to the full. Fortunately, solar radiation and ambient temperature are coupled by their causality. However, ambient temperature lags solar radiation throughout the day.

An ejector operating with a fixed primary nozzle throat diameter is not able to fully utilise the ambient temperature lag in the morning because the nozzle enthalpy is rate limited by the nozzle pressure. Increasing nozzle pressure, and also temperature, to overcome this limitation simply results in lower collector efficiency and reduced entrainment ratio in the ejector. Conversely, in the afternoon, the high ambient temperature demands an increased nozzle power and a nozzle with fixed throat diameter may demand more power than the collector is able to deliver. This leads to the standard ejector design practice of sizing the ejector for the highest ambient temperature expected and therefore condemns the ejector to low annual cooling yield.

Solar cooling systems often use thermal storage for solar heat to increase solar collector utilisation and to provide a temperature buffer to the vapour generator. However, there are undesirable exergy losses and cost penalties associated with thermal storage that may be avoided by direct actuation of the primary nozzle.

Nozzles with variable throat diameter have been proposed (Kim et al., 2006; Varga et al., 2009; Yen et al., 2013; Ma et al., 2010; Zhang et al., 2010). All of these nozzles use tapered needle jets inserted into the primary nozzle throat to alter the effective hydraulic diameter of the throat.

Yen modelled an ejector operating with refrigerant R145fa over a narrow range of condensing temperatures (35–40 °C) and vapour generator temperatures (90–110 °C). A correlation was produced for the ejector area ratio based on the ejector generator, evaporator and condenser temperatures. This correlation was based only on the varying nozzle throat diameter. However, the correlation was based on CFD and experimental data and so cannot be generally applied to other ejectors.

Despite an ideal gas model being used in the CFD modelling, excellent agreement with experimental data was noted by Yen. The results suggest that a variable primary throat will be an essential component of a high performance and cost effective ejector. In each of these variable nozzle designs, only the primary nozzle throat diameter is actuated. None of the designs attempt to actuate the nozzle exit diameter in a calculated manner.

Some insights are provided into the important effects of using the correct nozzle exit diameter by Huang et al. (1999). Although a range of experimental data is provided with this paper, direct comparison between primary nozzle effects is not possible because of changes in condenser and