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Experimental study of a low grade heat driven ejector cooling system using the working fluid R245fa

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ABSTRACT

Operation and performance evaluation of an ejector based refrigeration system subjected to external constraints and allowing for components interactions to be accounted for is presented. In this respect and relying on the identified most influential parameters, effects of generator conditions in terms of superheat, pressure and flow rate resulting from the imposed heat source temperature constraints on the condenser and evaporator conditions are shown to affect ejector operation efficiency as well as overall system performance. More particularly, the system is found to have two modes of operation corresponding respectively to ejector double choking (on design) and single choking (off design). In the first mode the system operation is stable with fixed thermal load and constant evaporator temperature. In the second mode, only the primary nozzle is choked, corresponding to less operation stability and variable temperature conditions in the evaporator with fixed thermal load.

1. Introduction

As worldwide interest in renewable and carbon neutral energy resources hits record levels, industrial waste heat is being overlooked as an emission-free source of energy. It is estimated that 20–50% of industrial energy input is released to the atmosphere through stacks, vents and flares. Table 1 summarizes typical major waste heat sources along with temperature range and characteristics of the source (Thekdi and Nimbalkar, 2014).

As the industrial sector continues efforts to improve its energy efficiency, recovering waste heat losses and convert them into cooling provides an attractive opportunity for a clean and low cost energy source. Indeed, the use of heat-driven refrigeration systems provides a promising alternative to substitute mechanical vapour compression systems in many cooling application instances. Thus, greenhouse gases (GHG) emissions are reduced by displacing electricity which is mainly generated by fossil fuels. In this context, ejector refrigeration technology seems to be a good candidate for heat recovery applications such as capturing the value of waste heat by cooling industrial hot streams (Yapici and Yetisen, 2007; Xiangjie et al., 2013; Jianyong et al., 2015 and Besagni et al., 2016). Consequently, the energy intensity of the process decreases and hence the productivity increases. Ejector advantages ensue from its reliability, long lifespan, low operating and maintenance costs (O&M). The drawback of this technology is the unfortunate combination of its low efficiency and design complexity. Poor performances are mainly due to irreversibilities occurring within the ejector and the fluctuations of operation, particularly in conditions of off-design. The highly complex internal ejector flow structure has not yet fully clarified its operation as part of a system despite increasingly extensive ground breaking work, and most existing experimental literature does not provide any information about ejector operation in full interaction with other system components under various conditions. It is therefore necessary to deepen the understanding of the impact of the driving parameters on ejector operation and the system's performances as a whole by way of experiments.

In the last decade, numerous experimental analyses on ejectors using a variety of working fluids have been reported in the open literature. Selvaraju and Mani (2006) studied several ejector sizes working with R134a for the influence of generator, condenser and evaporator on performance. Eames et al. (2007) tested their ejector with R245fa for the effects of nozzle geometry and position which they have shown to substantially affect performance. Yapici et al. (2008) used R123 to experiment on six cases of ejector area ratio within a range of imposed conditions at the ejector outlet and inlets in order to maximise performance. They varied ejec-

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Nomenclature

COP	coefficient of performance
CR	compression ratio
ER	entrainment ratio
ERS	ejector refrigeration system
H	enthalpy [kJ kg^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
P	pressure [kPa]
$\dot{Q}$	rate of heat flow [kW]
T	temperature [°C]
$\dot{W}$	power input [kW]

Subscripts

c	condenser
e	evaporator
g	generator
h	heat source
l	thermal load
m	mechanical
p	pump
s	sink
t	thermodynamic

tor efficiencies in order to match experiments with theory and concluded that for their system, a value of 0.9 represented best their results. Smierciew et al. (2014) and Butrymowicz et al. (2014) investigated solar and low-temperature driven ejectors with isobutane. Their system's COP at generating temperatures below 75 °C was in the range 0.15–0.19. Pereira et al. (2014) also experimented with Isobutane (R600a) using a variable geometry ejector by means of a spindle and a movable primary nozzle. Preliminary results indicated that combination of spindle and nozzle positions considerably affected ejector performance. Del Valle et al. (2014) tested with R134, three different mixing chambers and the nozzle relative position under several operating conditions, including primary-secondary superheats, for their effects on ejector performance. Shestopalov et al. (2015) with R245fa did further work on a fixed geometry ejector under fixed primary and secondary temperatures. The resulting data were presented in the form of conventional charts for the critical performance. Li et al. (2016) further investigated geometry variations, by means of a movable spindle while fixing inlet pressures and some superheat. As a result, cooling capacity was found to improve by up to 12%. Thongtip and Aphornratana (2015, 2017), proposed an analysis of ejector cycles based on the variation of the evaporator temperature associated with the cooling load supplied at the prevailing generator temperature and condenser pressure. This approach is more realistic than the conventional method of representing ejector performance curve, which may not adequately represent the performance of an ejector-based heat pump actual operation. They argued that the conventional method required precise control of ejector inlet temperatures and outlet pressure, a condition not fulfilled in real operation where the cooling load supplied to the evaporator is a variable parameter. Their tests with R141b on a fixed ejector geometry allowed identifying the lowest evaporator temperature corresponding to ejector double choking which coincides with the condenser critical condition in the conventional approach. Consequently, it was also shown that the increase of the primary mass flow rate, while causing the entrainment ratio to decrease, either increased the critical condenser pressure as indicated by conventional analysis or the evaporator temperature to decrease as determined by the alternative method. More recently and along the same lines, the authors also experimentally assessed the geometrical effect of the primary nozzle on ejector performance.

Most of the previous works focused solely on the effects of geometry and operating conditions on ejector performance in order to characterize it as a component independent of the system in which it was tested by artificially imposing fixed conditions at its inlets and outlet. The effect of operating conditions (generating, condensing and evaporating temperatures) was studied by varying one parameter and setting the others to constant values. These studies investigated the ejector performances in the double and the single choking operating regions (i.e. design and off-design operations respectively). However, less attention was accorded to study the behaviour of the ejector refrigeration system (ERS) under the mutual interaction between these governing parameters. Indeed, in the current literature, information is still scarce regarding the influence of generating pressure (i.e. primary mass flow rate) on other parameters. It appears that very little work on this issue is currently available. Zegenhagen and Ziegler (2015) published a study dealing with the development of an automotive air-conditioning system using the refrigerant R134a. The authors designed and operated an ERS capable of generating up to 6 kW of cooling. They mapped the system's performances by deriving correlations for both the thermodynamic and mechanical coefficients of performance as well as for the cooling capacity as a function of the entrainment ratio and generating pressure. They were able to characterize the system by producing a chart that linked the generating, condensing and evaporating pressures. To the authors' knowledge, this is one of the very few studies that adopt a system's (rather than a component's) approach in the study of ejectors.

Despite the tremendous work performed in the area of ejectors, there is still a lack of studies that adopt a systemic approach and more efforts are needed for a thorough understanding of the interaction between the different governing parameters and their combined effect on ERS performance. Actually, Thongtip and Aphornratana (2015) pointed out that the effect of the generating pressure

Table 1
Temperature range and characteristics for industrial waste heat sources.

Waste heat source	Temperature range (°C)	Cleanliness
Furnace or heating system exhaust gases	315–1100	Varies
Gas (combustion) turbine exhaust gases	480–600	Clean
Reciprocating engines		
Jacket cooling water	90–100	Clean
Exhaust gases (for gas fuels)	480–600	Mostly clean
Hot surfaces	65–315	Clean
Compressor after-inter cooler water	40–80	Clean
Hot products	100–1370	Mostly clean
Steam vents or leaks	120–315	Mostly clean
Condensate	65–260	Clean
Emission control devices – thermal oxidizers…	65–815	Mostly clean