

Solar-Driven Thermal Management Research at UKZN

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A variety of two-phase thermal management systems have been proposed in the literature, many of which rely on a pump to circulate the fluid through the system. This paper presents various solar assisted cooling systems and details a new thermally pumped refrigeration loop under joint development by the University of KwaZulu-Natal (UKZN), the University of Florida and Cairo University, that does not require a mechanical compressor, operates independently of gravity and is therefore suitable for both terrestrial and space applications. A common feature of many of these systems is the ejector which is a mixing device but also provides compression to the low pressure stream. Further research into ejector design for two phase unsteady flow is discussed as it is the limiting component of the system.

Keywords: Cooling, Ejector, Pulse, Refrigeration

Nomenclature

A_1	= nozzle exit area	m^2
A_3	= area of constant area mixing chamber	m^2
A_t	= nozzle throat area	m^2
d_t	= diameter of nozzle throat	m
dP	= pressure differential between boilers	bar
T_0	= total temperature	K
h_0	= total enthalpy	kJ/kg
L_x	= distance from nozzle exit to mixing chamber	m
L_3	= length of constant area mixing chamber	m
\dot{m}	= mass flow rate	kg/s
P_0	= total pressure	bar
$P_{1,2}$	= static pressure in boiler 1,2	bar
P_{sys}	= system pressure	bar
q	= heat	W/m^2
ECS	= Ejector Cooling System	
PRS	= Pulse Refrigeration System	
VCR	= Vapour-Compression Refrigeration	

1. Introduction

COOLING systems are necessary in mid-latitude sunny regions where a plentiful supply of solar radiation can be exploited. Solar thermal energy is the most abundant source of renewable energy available where approximately $1.08e14$ kW reaches the earth's surface (Thirugnanasambandam et al., 2010). A thermally driven cooling system, like the Pulsed Refrigeration System (PRS) described here, would be well-suited to rural areas of South Africa without access to grid electricity and could also reduce power consumption in urban areas. Concentrating solar collectors or industrial processes that produce significant amounts of low grade thermal energy can be used as a heat source.

A number of solar assisted refrigeration systems are found in literature, many of which incorporate ejectors. Ejectors have no moving parts and utilise a high pressure stream to entrain and pressurise a low pressure stream. Ejector-based cooling systems (ECS) offer the advantage of simplicity by eliminating the need for a compressor in the refrigeration part

of the cycle. Most ejector based systems, whether driven by solar or waste heat, require the refrigerant to be circulated either by an electric pump (Abdulateef et al., 2008) or a significant pressure head between the cold and hot sides (Nguyen et al., 2001).

The solar integrated thermal management and power (SITMAP) cycle proposed by Nord et al. (2001) is a combined thermal management and power producing system. A turbine is powered by waste or solar thermal energy which produces electrical power to drive a compressor or other electronic equipment. An ejector compresses the flow rather than a conventional compressor. The SITMAP system was further investigated by Zheng and Weng (2010) who simulated the cycle performance. An evaporating temperature of 280K is achievable with a 395K generating and 290K condensing temperature. Weislogel et al. (2002) developed a pulsed thermal loop (PTL) for cooling in aerospace applications. Driving pressures in excess of 18 bar are achieved through large pressure differentials of coupled boilers that absorb waste heat and are cyclically pulsed.

The current focus of thermal management research at UKZN is a proposed ejector-based solar-driven PRS that eliminates the requirement of a circulation pump in a cooling system. In conjunction with the University of Florida and Cairo University, we aim to develop a two-phase, active cooling system which combines the technologies of the SITMAP cycle and the PTL. The PTL boilers are similar in design to a multi-function generator, MFG, (Huang et al., 2006, Wang et al., 2009) however are more compact and well suited for terrestrial and gravity free applications. The compact design lends itself to small scale applications such as high powered electronic component cooling or household refrigerators.

2. Review of Current Technologies

Various types of refrigeration technologies include the vapour-compression, ejector-based, sorption and hybrid refrigeration cycles. For these systems a great amount of energy is associated with the phase change of the working fluid which enables heat ingress at the evaporator to achieve the cooling effect (Moran, 2006). These systems can be solar assisted to reduce power consumption and is the focus of many studies (Abdulateef et al., 2008, Fan et al., 2007, Kim and Infante Ferreira, 2008). The two common methods for obtaining cooling from waste or solar thermal energy resources include; (i) sorption systems which comprise of absorption and adsorption cycles that produce cooling from chemical or physical interactions between sorption pairs (Fan et al., 2007, Kim and Infante Ferreira, 2008, Li et al., 2008) and (ii) ejector-based systems where the ejector provides the compression rather than an electric compressor in a vapour-compression refrigeration (VCR) cycle (Cizungu et al., 2005).

2.1. Basic Vapour-Compression Refrigeration Cycle

Cooling is most commonly achieved with vapour-compression refrigeration (VCR) shown in Figure 1. The system comprises of four essential components; an electric compressor, condenser, expansion valve and an evaporator. The condenser and the evaporator are isobaric heat exchanging devices. Refrigerant is expanded at constant entropy through the expansion valve, lowering the temperature at the evaporator. Heat is removed from the cold space by refrigerant that is circulated with a compressor. The compressor raises the pressure of the refrigerant at constant entropy to enable the vapour to condense at the condenser.

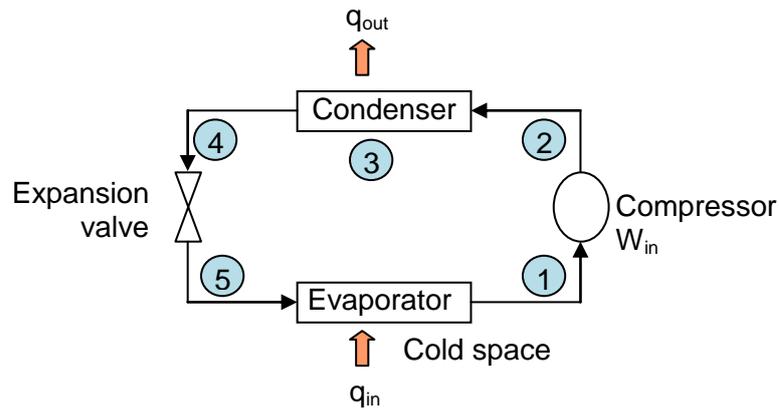


Figure 1. Single stage vapour-compression refrigeration cycle (du Clou, 2010)

2.2. Ejector Cooling System

Environmental considerations have prompted researchers to investigate ejector cooling systems (ECS) (Abdulateef et al., 2008, Eames et al., 1995, Cizungu et al., 2001) although their COP values are comparably lower than that of the conventional compressor driven cycle. The ECS, detailed in Figure 2, can be powered by low grade heat energy. The main component of the ECS is the ejector which has no moving parts and hence does not require maintenance. Although the ECS is promoted as a renewable system, it still requires a circulation pump. Nguyen et al. (2001) developed a pump-free ECS where the low pressure side (condenser) was elevated to a 7 m head. This provided the pressure necessary to return the working fluid to the high pressure generator. Such a system is cumbersome in design and would be unsuitable for micro-gravity applications.

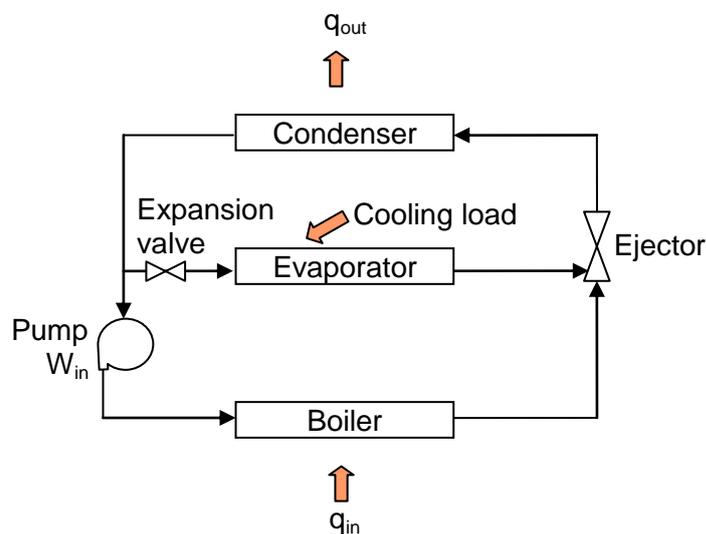


Figure 2. Schematic of ejector cooling cycle (du Clou, 2010)

2.3. Solar Powered Refrigeration

Solar energy can be utilised as a thermal heat source or converted to electrical energy to power a refrigeration cycle. Such systems are more complex than conventional VCR systems (Figure 1) and often do not increase the COP however are able to reduce electrical power consumption. The energy savings result in a decreased load on the electricity grid.

2.3.1. Solar Electric Refrigeration

Solar electric refrigeration systems incorporate photovoltaic cells which provide electric power to the system (Figure 3), driving the compressor of a conventional VCR system. The overall system efficiency is reduced due to the low efficiency of photovoltaic solar panels, which are often less than 15% (Kim and Infante Ferreira, 2008). If a VCR system has a COP of 2.5 and is coupled with a solar electric power source having an efficiency of 15%, the resultant system efficiency would be only 37.5%. The reduced COP might be considered acceptable since the work input to the compressor is free.

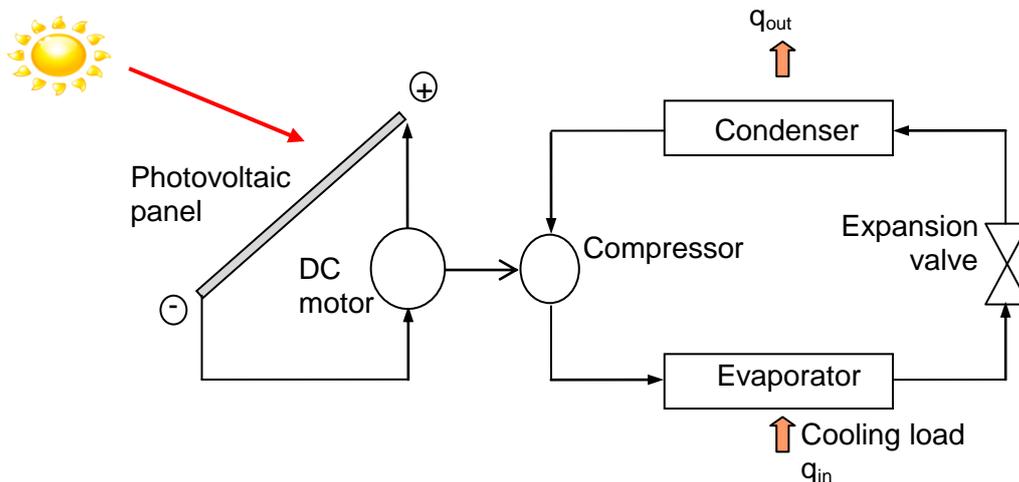


Figure 3. Solar electric powered refrigeration system (Kim and Infante Ferreira, 2008)

2.3.2. Solar Thermal Refrigeration

Rather than convert solar thermal energy into electrical energy and then to mechanical work, the thermal energy can be used directly to drive a cooling system. A flat plate solar panel, evacuated tube solar panel or a high powered concentrating solar collector (Mouzouris, 2009) could be coupled to a sorption or ejector cooling system to provide the required thermal energy. The thermal energy is transferred to the working fluid generating the driving pressure in the system. The driving pressure can be used to create work and circulate the refrigerant.

3. An Ejector-Based Solar-Driven Pulsed Refrigeration System

The proposed ejector-based PRS is derived from two recent concepts; the Pulse Thermal Loop (PTL) (Weislogel, 2002, Weislogel, 2004), providing the high driving pressure, and the Solar Integrated Thermal Management and Power (SITMAP) system (Nord et al., 2001, Zheng and Weng, 2010, Kandil et al., 2004) which enables cooling at the evaporator.

3.1. Solar Integrated Thermal Management and Power (SITMAP) System

The ejector-based SITMAP cycle in Figure 4 is driven by a solar-powered pump-turbine combination and is intended for space applications. The SITMAP system combines a cooling cycle with a power producing cycle (Nord et al., 2001, Zheng and Weng, 2010, Kandil et al., 2004). The ejector provides the compression in the refrigerator subsystem rather than a compressor and mixes the flow of the two streams. The system is driven by the power produced at the turbine which in turn is driven by solar thermal energy.

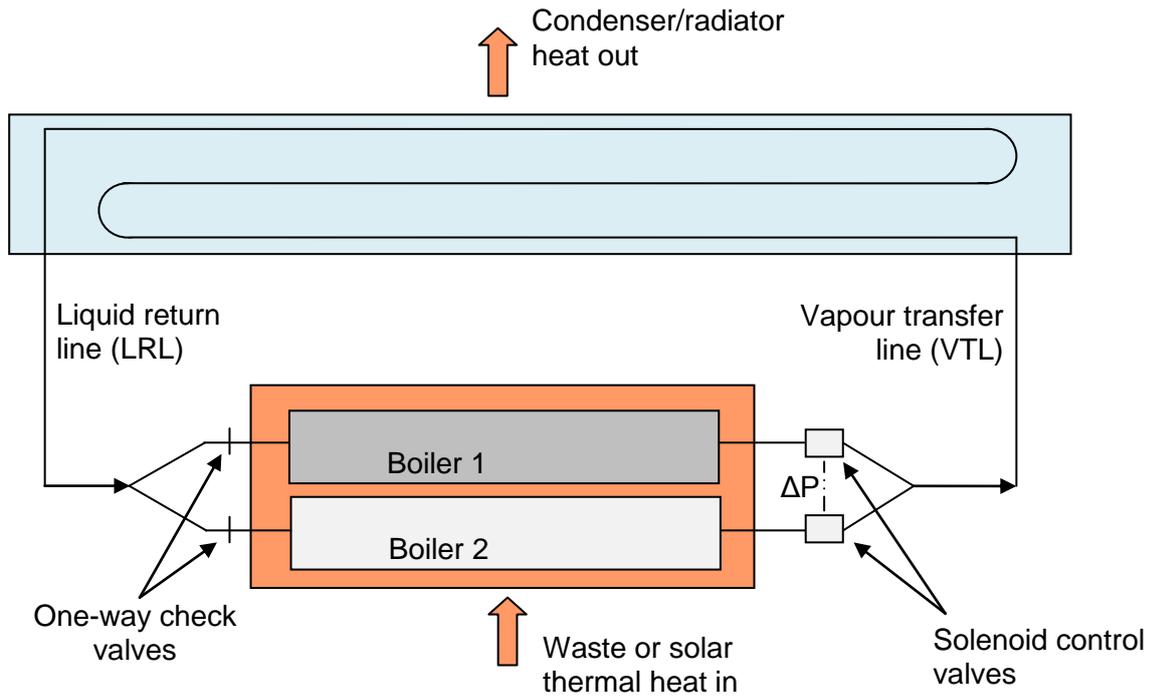


Figure 5. Schematic of a Pulse Thermal Loop (du Clou, 2010)

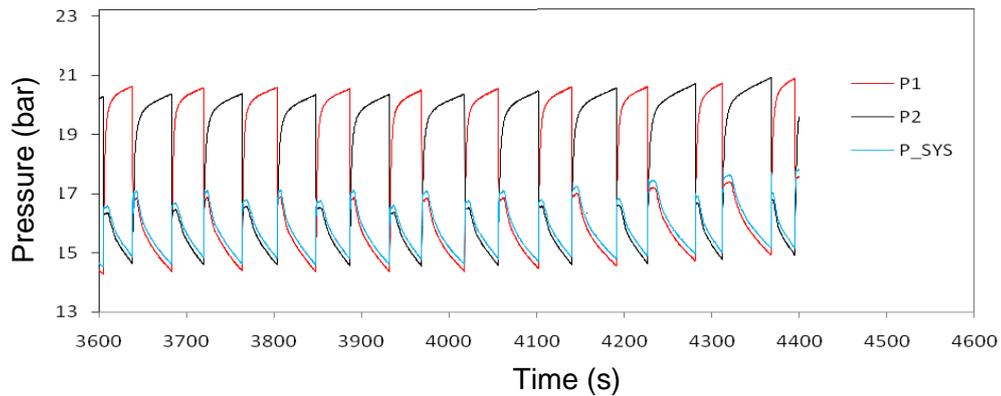


Figure 6. Experimental data from a pulse thermal loop showing boiler pressures (P1 and P2) that rise and fall in response to toggling of outlet solenoid valves. The pulses propagate through the system and die out as the vapour condenses (du Clou, 2008)

Table 1. Pulse Thermal Loop design characteristics

Characteristic	Weislogel et al. (2004)	Brooks et al. (2008)
Working fluid	R-134a	R-134a
Volumes	Boiler: 44.8 cm ³ , Condenser: 27.88 cm ³ , VTL: 19.7 cm ³ , LRL: 14.91 cm ³ , Total: 152 cm ³	Boiler: 63.0 cm ³ , Condenser: 39.2 cm ³ , VTL: 27.7 cm ³ , LRL: 21.0 cm ³ , Total: 213.9 cm ³
Charge level	$V_{\text{vapour}}/V_{\text{total}}$: 0.594-0.807 @ 20°C	Refrigerant mass of 80 to 120 g
Transport tubing	4.82 mm ID	4.55 mm ID

Transport tubing length	3.3 m	4.2 m
Q range	25 – 1200 W	-
ΔP range	0.5 – 16.5 bar	0.5 – 18 bar
Boiler type	Two copper blocks 305 mm long with 12.7 mm cylindrical hole and heated by a cartridge heater.	Two thermally uncoupled aluminium blocks, with 15 mm cylindrical hole and 500 W cartridge heater per block.
Condenser type	Serpentine, counter flow, water cooled	Counter flow, water cooled
Instrumentation	3-way solenoid valves	Type-K thermocouples, Wika S-10 and A-10 pressure transducers, 2-way solenoid valves

4. System Layout

The PRS proposed by Brooks et al. (2009) is a two-phase, active cooling system which combines the technologies of the SITMAP ECS and the PTL. Replacing the SITMAP pump-turbine combination with a pair of PTL constant volume boilers results in a pump-free refrigeration system that can be powered primarily by solar energy. Whereas earlier work conducted in the School of Mechanical Engineering focused on the design of a PTL (du Clou, 2008, Brooks et al., 2008), this work aims to develop the PRS.

A schematic of the PRS is shown in Figure 7. There are two loops; the outer driving loop and a cooling loop. The heat source to the boilers is simulated using 100 Watt electrical heaters which can be replaced by a Fresnel collector coupled with a fibre optic transmission cable being developed by Mouzouris et al. (2009). A sustained series of high pressure pulses is generated by alternately isolating, pressurising and pulsing refrigerant (R-134a) through the system (similarly to a PTL). Check valves are used to eliminate back flow of refrigerant within the system. Solenoid valves are triggered with LabVIEW software to control the flow of refrigerant through the system. The ejector entrains secondary flow from the refrigeration loop and provides the compression in the refrigeration sub-system. The water cooled condenser removes heat from the system and provides slightly sub-cooled refrigerant to the boilers and the cooling loop.

Extensive research has been carried out on ejectors in an effort to improve their design and performance for application in an ECS (He et al., 2009, Rusly et al., 2005, Sherif et al., 2000, Zhu et al., 2009, Zhu et al., 2007, Cizungu et al., 2005). Mostly, the literature focuses on single and two-phase ejectors in steady state operation. A requirement of this study is that the ejector should accept unsteady flow from the pulsed boilers, therefore analysis and testing of an appropriate design able to function under transient flow conditions in the PRS must be addressed. At present a two-phase model of ejector performance is under development using MATLAB and the materials database, RefProp. This model will be used to investigate off-design performance, using a quasi-steady state approach. The ejector model will be fed with varied off-design input flow conditions at the primary nozzle to determine an overall picture of its 'transient' response. Once a suitable transient ejector design has been completed, a full prototype of the ejector-based refrigeration system will be constructed and tested.

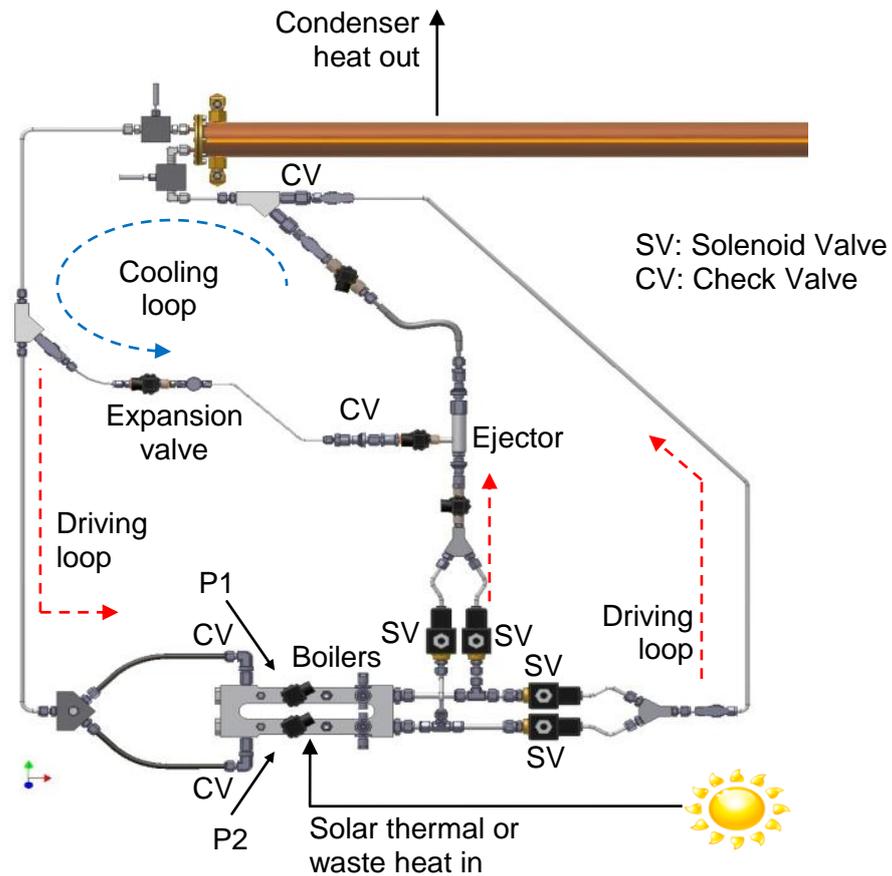


Figure 7. Schematic of Ejector-Based Solar-Driven Pulsed Refrigeration System (du Clou, 2010)

5. Ejector Design

An ejector consists of four main components; the nozzle at the primary inlet, the suction chamber housing the secondary inlet, the constant-area mixing chamber and the recovery diffuser (Figure 8). The primary flow isentropically expands and accelerates through the convergent-divergent nozzle to reach supersonic velocity (process 0-1). The secondary flow is entrained into the lower pressure suction chamber (point e). The primary and secondary flows then mix in the mixing chamber (process 2-3) where a shock wave forms and pressure is mostly recovered. The resulting stream regains pressure in the diffuser (process 3-c). The process of optimising the ejector design is presented in the flow chart, Figure 9.

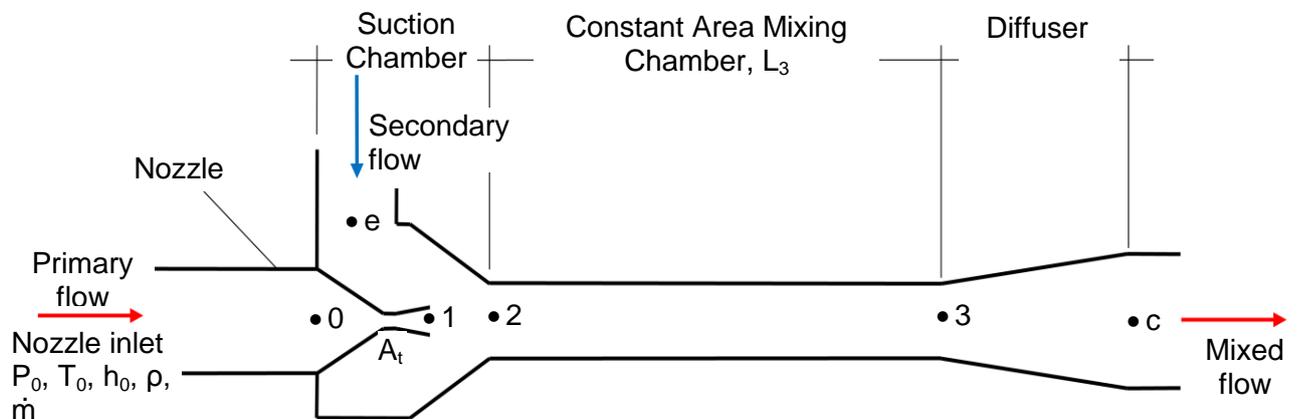


Figure 8. Ejector design schematic (du Clou, 2010)

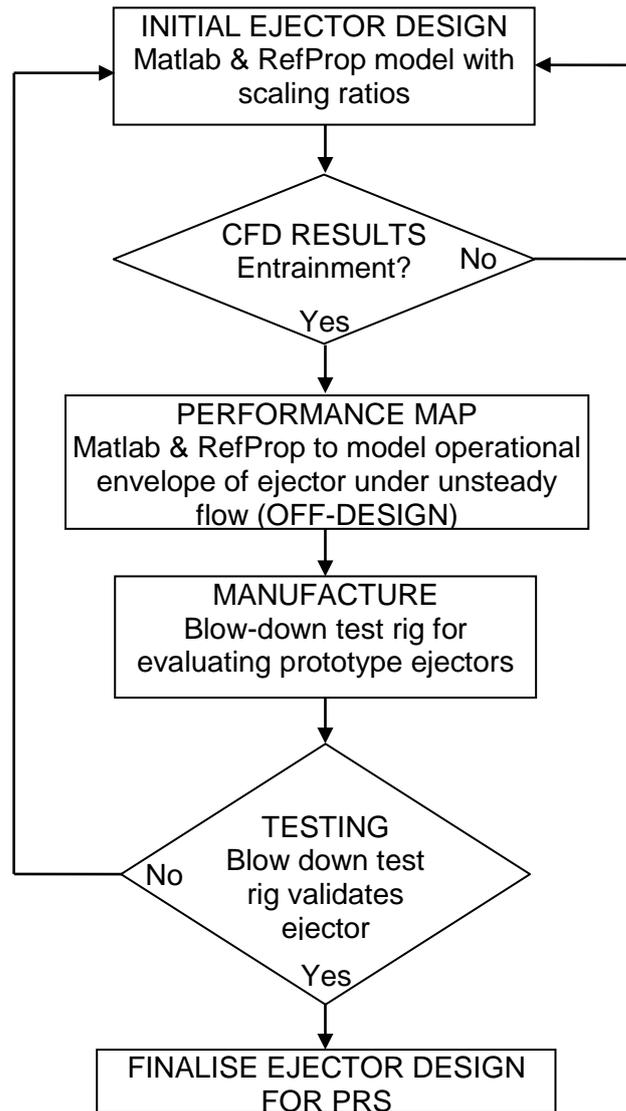


Figure 9. Iterative design methodology for optimising ejector performance in a PRS (du Clou, 2010)

6. Conclusion

A range of solar-driven thermal management systems has been described, including a novel ejector-based system that operates independently of a conventional pump. Such a cooling system would benefit the environment by reducing demand on the electricity grid. By eliminating a compressor, the pulsed refrigeration system described here reduces system complexity. A unique feature of the PRS is transient flow through the ejector, requiring new approaches to the design of this component. A functional ejector capable of operating under variable input pressure is essential to the operation of a proposed system, and is now the subject of ongoing research. An optimised ejector would make possible a pump-free cooling system driven either by waste heat or solar energy.

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