Design of a Solar-Driven Ejector Cooling System

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Abstract
The Pulse Refrigeration System, or PRS, is a heat transfer and cooling system that may be powered by solar or waste heat. The engineering prototype comprises a stack of constant volume boilers, a counter-flow shell and tube heat exchanger, an ejector and data acquisition hardware and software. The ejector replaces a compressor that is normally required in the cooling part of the cycle, reducing energy consumption. It is a mechanically simple device that enables the mixing of two streams, where the motive flow entrains and compresses the lower pressure secondary stream. The primary inlet to the ejector is supplied with unsteady pressure pulses from the boilers and the resulting flow is predicted using an analytical quasi-steady model implemented in MATLAB, incorporating real vapour data sub-routines. The ejector modes of operation are investigated during the transient highlighting the requirement of system valve timing in order to maximise performance.

Keywords: Solar, Cooling, Refrigeration, Ejector, Transient

Nomenclature

A	=	area	m^2
CD	=	converging-diverging nozzle	
d	=	diameter	m
L	=	length	m
M	=	Mach Number	
$\dot{m}$	=	mass flow rate	g/s
P	=	pressure	bar
PRS	=	Pulse Refrigeration System	
Pr	=	pressure ratio across CD nozzle	
PTL	=	Pulse Thermal Loop	
q	=	heat	W/m^2
x	=	quality	

Greek letters

ω	=	entrainment ratio, $\dot{m}_s/\dot{m}_p$	
ψ	=	ejector compression ratio, P_c/P_{s0}	

Subscripts

e	=	converging diverging nozzle exit property
is	=	isentropic
m	=	property after mix
p	=	primary inlet property
s	=	secondary inlet property
t	=	converging-diverging nozzle throat property
x	=	conditions before shock
y	=	conditions after shock
0	=	total stagnation property
1	=	property downstream of CD nozzle

1. Introduction

Renewable energy sources provide a sustainable alternative to reduce carbon emissions and our dependence on fossil fuels. Various heat transfer and cooling systems that can be powered by waste heat or solar thermal energy have been developed and are well suited

for areas experiencing high insulation levels or are off the electricity grid. Compressor based refrigeration systems could be powered by solar generated electricity, but the overall efficiency is reduced due to the unnecessary energy conversion from solar, to electric, to mechanical energy. Solar cooling systems powered primarily by direct solar thermal energy is therefore an attractive option and improved performance can be achieved with an increase in available solar radiation (Khattab and Barakat, 2002).

A number of thermally driven ejector cooling systems have been investigated where an ejector compresses the refrigerant to the condenser pressure rather than a mechanical compressor (Meyer et al., 2009, Abdulateef et al., 2008, Eames et al., 1995), but all require a circulation, or feed pump to operate. The Pulse Refrigeration System (PRS) described here does not require a feed pump. Instead it makes use of a stack of constant volume boilers that pulse refrigerant around a loop, similar to the Pulse Thermal Loop, or PTL (Weislogel, 2004).

The PRS design is currently limited by the performance of the ejector (du Clou, 2010). Secondary flow is entrained by the low pressure, high Mach number region that is formed at the outlet of the primary converging-diverging nozzle, in the suction chamber. The nozzle pressure ratio (Pr), suction chamber pressure over boiler pressure, increases during a pulse due to the emptying boiler that feeds it, reducing the velocity profile at the nozzle exit, limiting the entrainment. A variable geometry nozzle at the inlet to the ejector would solve this problem but the small scale and rapid reaction time required is unfeasible. A better understanding of the transient fluid dynamics is required in order to specify a suitable fixed geometry ejector that will enable entrainment over a range of driving pressures. This work presents an analytical model, implemented in MATLAB, to predict the performance of the ejector during transient operation and highlights the different ejector operating modes.

2.   Pulse Refrigeration System

The PRS design in Figure 1 comprises two loops. The outer loop is based on the PTL design where two boilers are alternately pressurised and pulsed to pump refrigerant in an anti-clockwise direction through transfer tubing, through the condenser and back to the adjacent boiler. An ejector is placed in line with the outer loop, after the boilers, and entrains refrigerant from the inner cooling loop. The ejector provides the compression required for the refrigeration part of the cycle. A notable feature is that the pump-free system can be powered by low grade waste heat or solar thermal energy. Variable flow is generated by the constant volume boilers which results in the ejector operating in an off-design condition for most of the pulse.
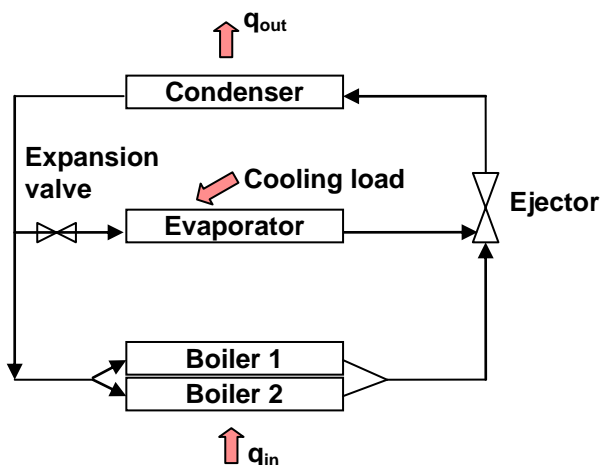

Figure 1. Pulse Refrigeration System schematic

3.   Ejector Design

The ejector is a mechanically simple mixing device which may be analysed using compressible flow theory. The ejector depicted in Figure 2 is comprised of the converging-diverging (CD) nozzle at the primary inlet, the suction chamber housing the secondary inlet, the constant-area mixing chamber and the recovery diffuser. Following compressible gas theory, the flow expands isentropically and accelerates through the CD nozzle to reach supersonic velocity (process 0-e) resulting in the low pressure region in the suction chamber. The secondary flow is entrained (process e-1) and undergoes Fabri chocking (Munday and Bagster, 1977) due to the hypothetical converging duct formed between the primary flow stream and the ejector wall. The primary and secondary flows mix during the constant pressure process (process 1-m). A shock wave forms in the constant area chamber if the ejector is operating under choked conditions (critical operation). The resulting stream regains pressure in the diffuser (process 2-c).

An ejector is defined using geometric ratios, pressure ratios and the entrainment ratio. The entrainment ratio (ω) is the ratio of the entrained secondary flow rate to the primary flow rate. The ejector compression ratio (ψ) is the ratio of the compressed downstream pressure to the entrained secondary pressure and is inversely proportional to the entrainment ratio. The entrainment ratio for an ejector in the PRS is anticipated to be very low due to the compression ratio which approaches unity.
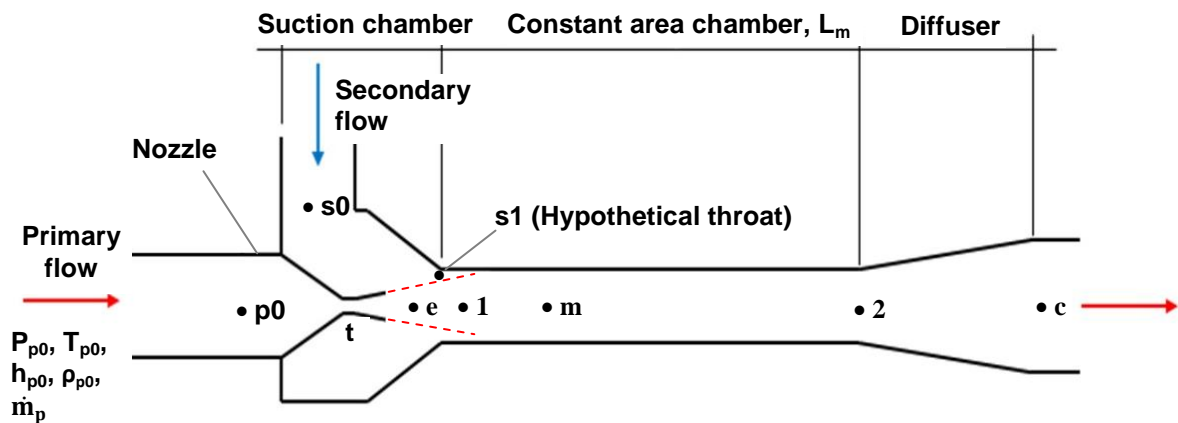

Figure 2. Ejector design schematic

4.   Ejector Design Model

The ejector design model developed in MATLAB generates the optimum geometry for steady state operation (constant flow rate). The model logic is depicted in Figure 3. The code is able to account for two phase flow and the fluid thermodynamic properties are referenced using NIST RefProp (Ver. 7.0) subroutines. Routine application of the governing equations solves the flow at each point along the ejector axis outputting the key dimensions. The non-isentropic normal shock wave is modelled by iteratively increasing the pressure across the shock wave, and finding the local fluid properties using conservation of mass and momentum for the control volume surrounding the shock, until the calculated density after the shock is equal to or greater than the reference density.
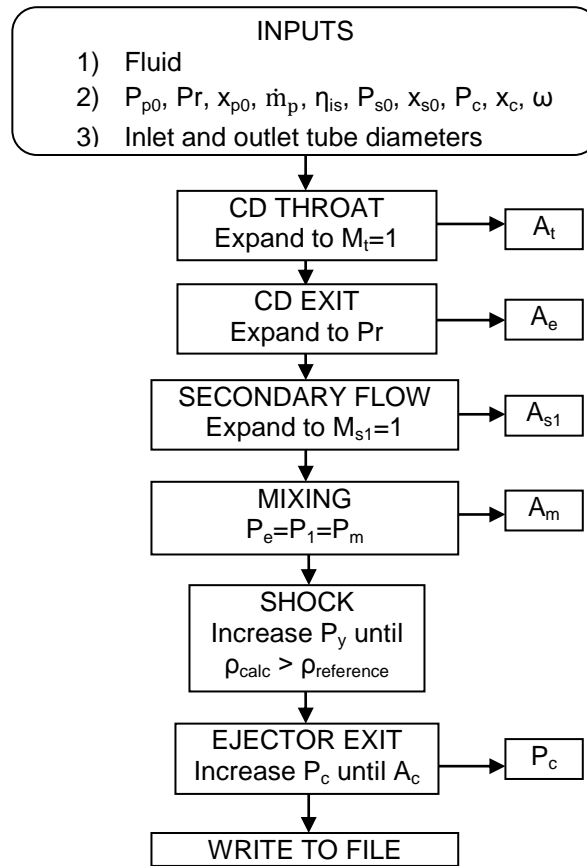
Figure 3. Design model logic diagram

4.1. Ejector Design Validation

The geometry generated using the one dimensional model is compared to the experimental data of Huang et al. (Huang et al., 1999) for validation. Refrigerant R141b is supplied at different generator pressures; 400 kPa, 465 kPa, and 537 kPa (saturated vapour) whilst the secondary inlet is maintained at 40 kPa. For a given generator pressure, three entrainment ratios are modelled resulting in a corresponding optimal area ratio (A_m/A_t) curve. Figure 4 presents the results by comparing the experimental and theoretical area ratios. The linear relationship validates the model which under predicts the experimental area ratio with a mean error 6%.
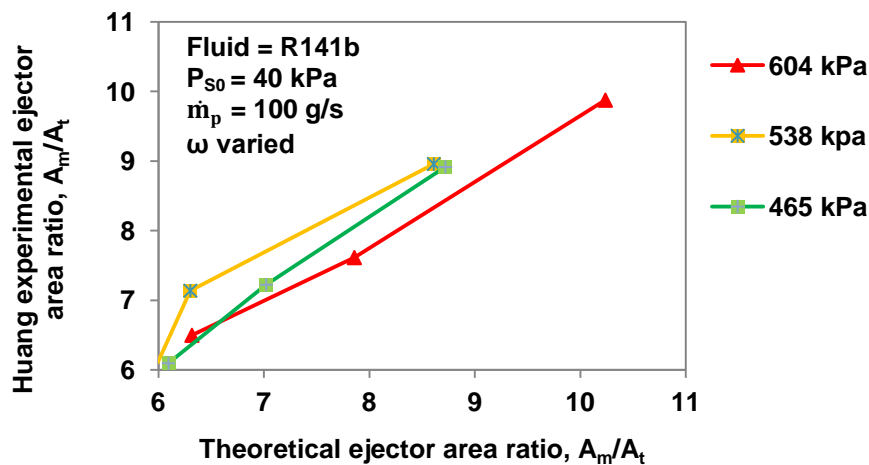

Figure 4. Area ratio for the design model is compared to the experimental results of Huang et al. (Huang et al., 1999). 1 bar = 100 kPa

In a PRS with a large enough feed boiler, the flow through the ejector would be considered steady, requiring a constant ejector area ratio. The PRS has a limited volume boiler and the ejector is therefore subject to a transient, blow-down effect characterised by an initially strong but decaying pressure pulse. The driving pressure decreases introducing unsteady flow and limits entrainment at the secondary inlet. A variable geometry nozzle would enable optimal operation during blow down by decreasing the divergent exit diameter to maintain supersonic low pressure flow at the outlet. Due to the small scale and manufacturing limitations of the ejector, a fixed geometry nozzle is to be designed and must enable adequate ejector performance for a range of driving pressures.

4.2. Ejector Design Results

Figure 5 illustrates the required ejector geometry in order to provide entrainment for different feed pressures from the supply boilers. At 18 bar supply pressure, the CD nozzle throat diameter is 0.92 mm, the CD nozzle exit diameter is 1.51 mm and the constant area duct diameter is 1.76 mm. If the supply pressure is decreased to 14 bar, the ejector CD nozzle throat, exit and mixing chamber diameter must increase by 13.6%, 12.6% and 9.5% respectively in order to maintain the required nozzle pressure ratio (Pr), entrainment ratio (ω) and mass flow rate.
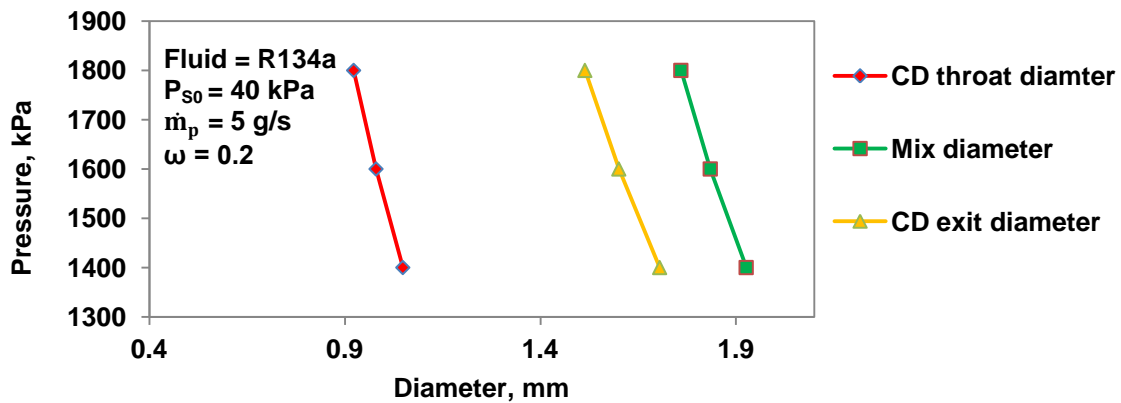
Figure 5. Geometry variation in response to different boiler pressures

Figures 6 and 7 give the results for an R134a ejector operating with a 16 bar primary and 4 bar secondary saturated vapour inlet pressure, primary mass flow rate of 5 g/s, an entrainment ratio of 0.2, and a CD nozzle Pr of 0.1. The tube diameters upstream and downstream of the ejector are constrained by the system in which it will operate. Here the primary inlet and outlet diameters are 1/4" (4.5 mm ID) with a 1/8" (1.8 mm ID) secondary inlet. The output to the model is the ejector geometry and the fluid properties at various locations along the ejector axis. One input variable (P_{p0}, P_{s0}, P_c, x_0, x_s, or $\dot{m}$) can be varied while keeping the others constant to obtain similar design graphs.

Figure 6 shows the ejector pressure profile in response to the geometry (cross section diameter) during steady operation. Figure 7 plots the pressure and Mach number profile along the ejector axis. The fluid expands to the 0.89 mm throat to reach sonic velocity. The flow continues to expand to the CD nozzle outlet at 1.45 mm. The secondary flow is then entrained and choked at its hypothetical throat formed between the core flow and the ejector wall. The primary and secondary flow then mixes at constant pressure to a mixed diameter of 1.65 mm. A shock wave in the constant area section (shown by vertical lines in the plot) raises the pressure of the working fluid and prevents the downstream condenser from communicating with the secondary inlet to the ejector. The diameter increases to the 4.5 mm diffuser outlet, resulting in further pressure recovery.
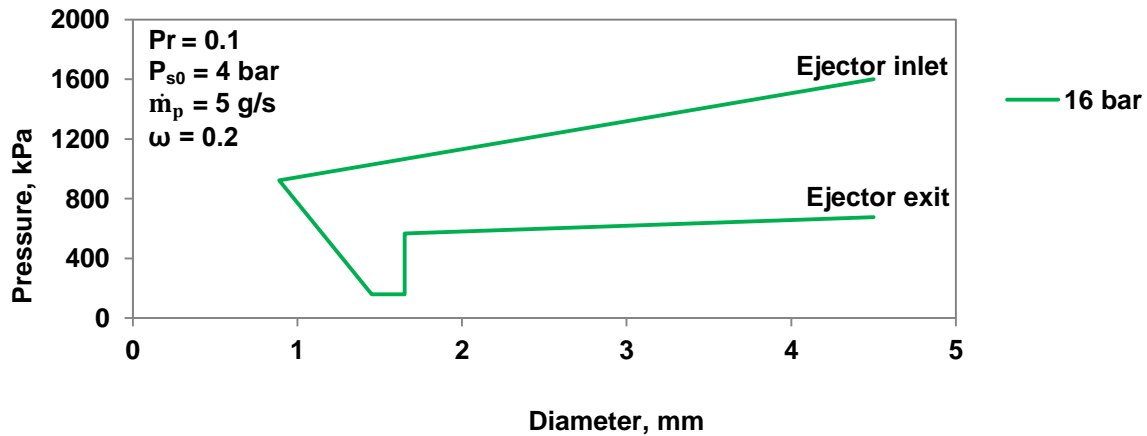
Figure 6. Static pressure profile versus ejector geometry in response to a steady primary inlet pressure of 16 bar (1600 kPa)
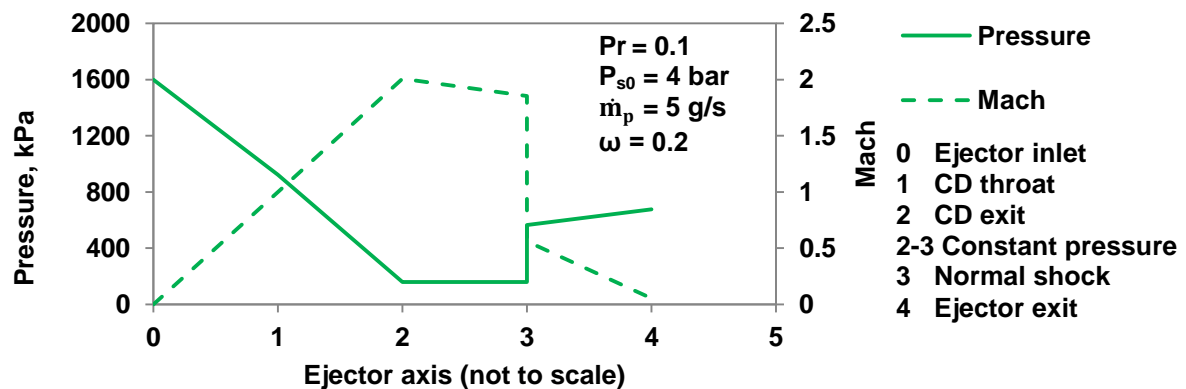

Figure 7. Static pressure and Mach number contours at different ejector axis locations in response to 16 bar primary inlet pressure and constant flow rate

5. Ejector Transient Model

The transient performance model solves for the operating parameters of a fixed geometry ejector that is fed by a depressurising boiler initially containing a fixed mass. The unsteady flow is assumed to be quasi-steady with the instantaneous flow properties being a function of time. At each incremental time step, a fixed mass of refrigerant leaves the boiler resulting in a decrease in feed pressure, temperature and density. Although the boiler block in a PRS would operate at a constant temperature, the rapid blow-down reduces the pressure of the refrigerant inside the vessel faster than thermal conduction and convection from the block to the refrigerant can take place. Therefore the boundary for the control volume of the fluid in the boiler is considered to be adiabatic, and it depressurises isentropically.

Since the under-expanded free expansion wave and the over-expanded shock train downstream of the CD nozzle cannot be captured using one-dimensional theory, only the CD nozzle at the inlet of the ejector is modelled for the transient regime. Once the flow through the nozzle is fully characterised, the rest of the ejector can be modelled using the design code. For an ejector to provide entrainment, the CD nozzle must fully expand the flow and avoid oblique and normal shock waves that produce entropy.

5.1. Transient Model Results

The results presented here are based on the geometry from the 16 bar design results giving a 0.89 mm throat and 1.45 mm exit diameter for the CD nozzle. An 80 cm^3 boiler

containing 7 grams of R134a, that is pressurised to 16 bar, and exhausted through the CD nozzle is simulated indicating the ejector operating modes and shock locations with respect to time. The back pressure (P_1) downstream of the CD nozzle is set to 2 bar.

Figure 8 graphs the operating modes during the transient blow-down; note the similarity to the well know operating modes of a CD nozzle. The quasi-steady approach tracks the shock location as it moves up the nozzle towards the throat. The cross section diameter at the shock can be read off of the x-axis. At 2.6 seconds (green trace) the normal shock is located at the 1.14 mm cross section. The oblique shock plotted (brown trace) is not an accurate representation of the flow because of one-dimensional flow assumptions. The Mach number at the throat, before the shock, after the shock, at the exit, and downstream of the CD nozzle is plotted in Figure 9. The flow downstream of the CD nozzle (M_1) remains supersonic for 1 second (31% of the blow-down) which will result in secondary entrainment. After 1 second, progressively stronger oblique shocks occur reducing the downstream Mach number, followed by normal shock waves inside the CD nozzle, limiting entrainment.
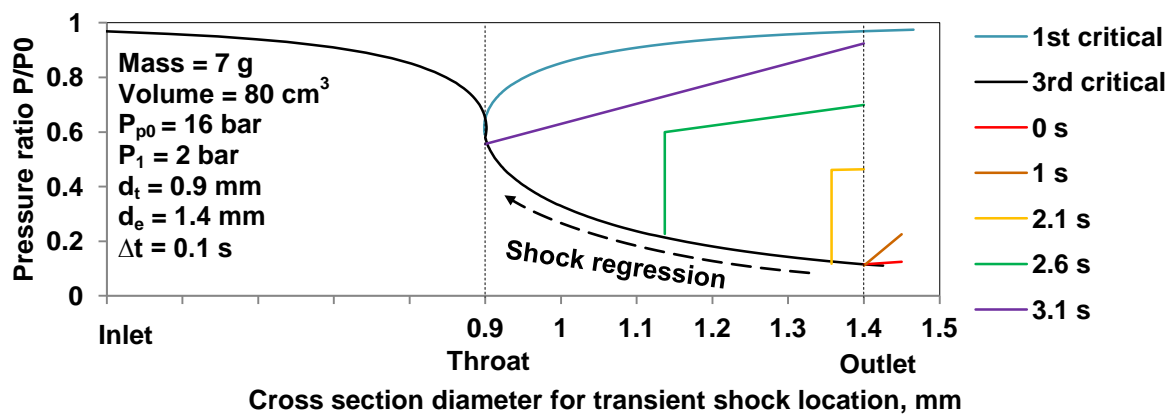

Figure 8. CD nozzle operating modes and shock location in response to an increasing pressure ratio during transient blow-down operation
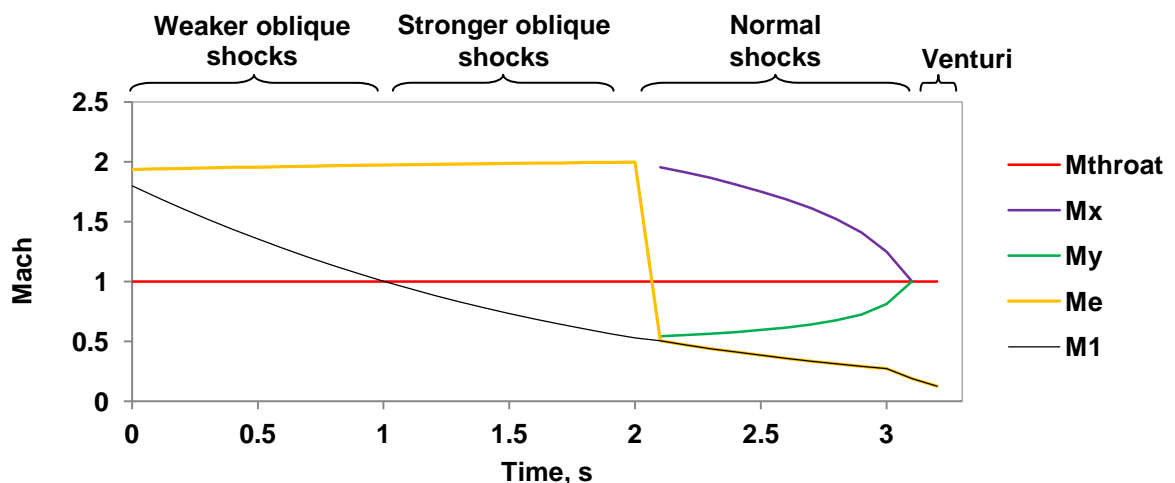

Figure 9. Mach number at different locations along the nozzle as a function of time during blow-down

5.2. Optimising the Ejector Geometry

Using the same operating conditions from the previous results, the performance model can be used to investigate variations in the ejectors' CD nozzle geometry and the effect on its operating modes. To ensure that the downstream flow is supersonic for a greater portion of the blow-down (hence reduce the period that shocks occur), smaller exit diameters are modelled. By reducing the CD nozzle outlet diameter to less than the steady state design condition of 1.45 mm, the flow is expected to initially be below the third critical point (under-expanded). This will ensure that the design condition is met at some time during the blow-down where the flow is perfectly expanded to the third critical P_r.

Figure 10 graphs the Mach number profiles for different CD nozzle outlet geometries subjected to the same blow-down conditions. As the outlet diameter is reduced, the period of downstream supersonic flow increases (period where $M_1 > M_t$), for the given back pressure (P_1).
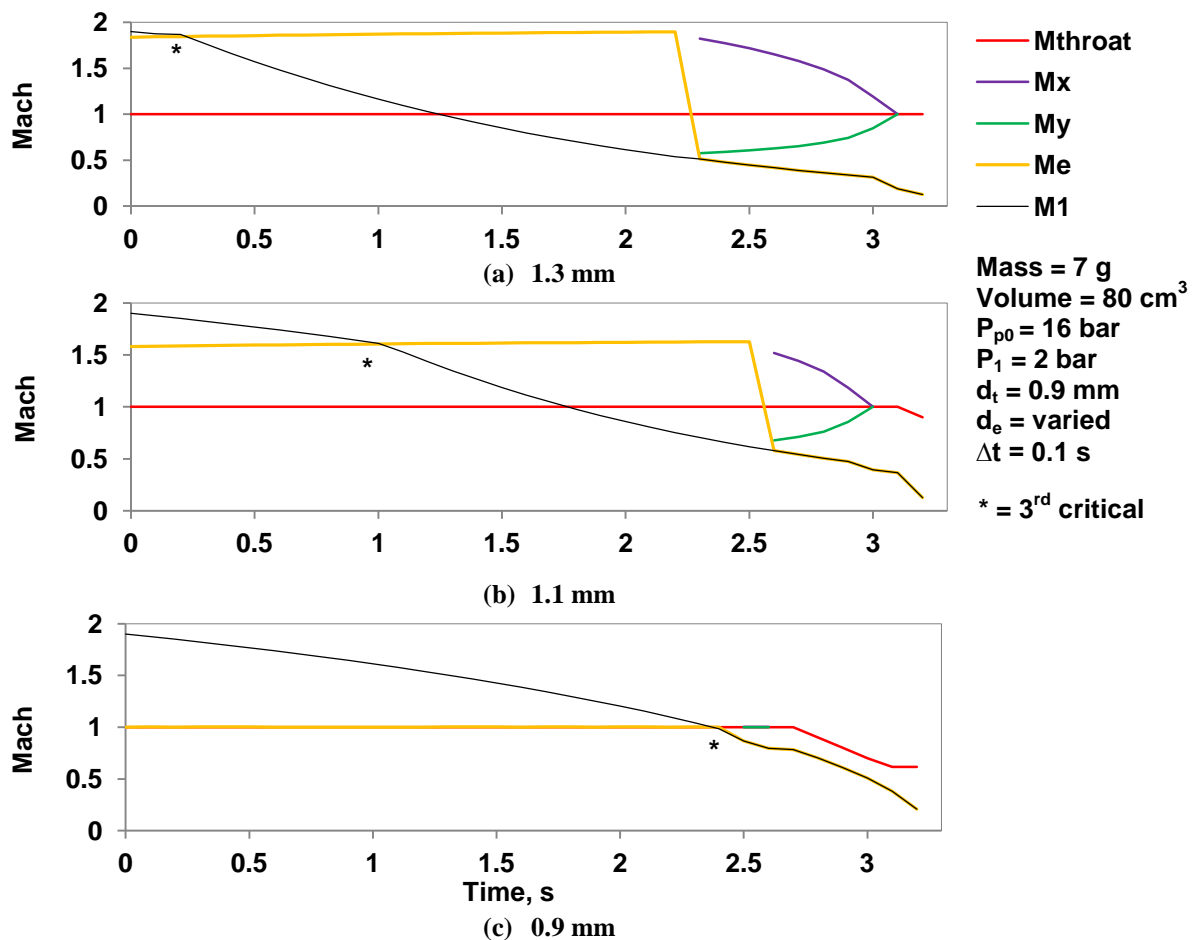

(a) 1.3 mm

(b) 1.1 mm

(c) 0.9 mm

Mass = 7 g
Volume = 80 cm^3
P_{p0} = 16 bar
P_1 = 2 bar
d_t = 0.9 mm
d_e = varied
Δt = 0.1 s

* = 3rd critical

Figure 10. Mach number profiles for different ejector CD nozzle geometries a) d_e=1.3 mm, b) d_e=1.1 mm, and c) d_e=0.9 mm. A smaller exit diameter results in an increased period of supersonic downstream flow, M_1

6.   System Valve Timing

From the results obtained it is evident that a suitably designed ejector will enable entrainment for a finite period, after which the ejector will operate with non-isentropic shock waves resulting in little to no entrainment. By incorporating valves, shown in Figure 11, in the proposed system control scheme, the ejector will operate for the first portion of the pulse exploiting the high pressure ratio across the CD nozzle. When the boiler pressure falls below a predetermined value the valves toggle such that the flow bypasses the ejector. For example, using the ejector geometry investigated in Figure 10 (b) the ejector is bypassed after 1.7 seconds of blow down.
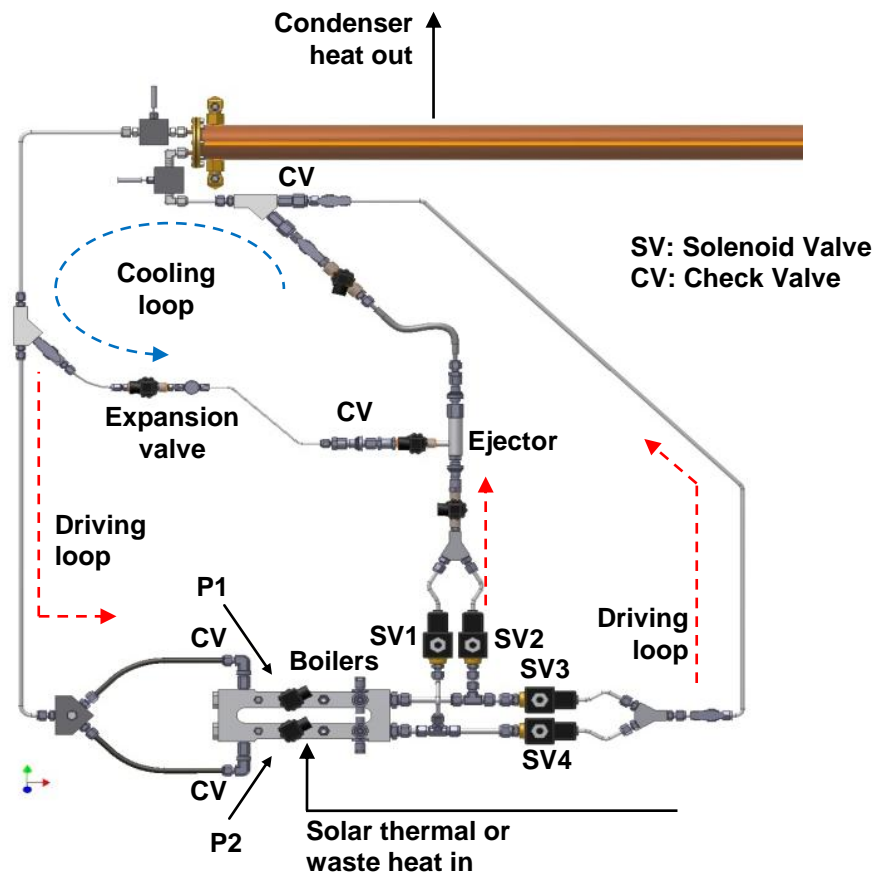

Figure 11. Schematic of Ejector-Based Solar-Driven Pulsed Refrigeration System (du Clou, 2010)

7.   Conclusions and Recommendations

Successful demonstration of the Pulse Refrigeration System depends on the performance of the ejector. A better understanding of the ejector and how it responds to transient inputs is required in order for it to be designed to function optimally during blow down operation.

The design and performance of an ejector for use under transient flow conditions is detailed using a two part, analytical, two-phase model. The design model accurately describes the geometry required for steady flow conditions. Different steady operating parameters are imposed to achieve specific ejector geometries. A selected design is then further investigated using the performance model. For an increasing pressure ratio (due to the depressurizing feed boiler) the flow rapidly becomes subsonic and results in zero entrainment.

The performance model is also used to investigate the result of varying the CD nozzle geometry for a given blow down condition. A smaller CD nozzle diverging exit diameter

results in a longer period of supersonic downstream flow and less shock waves. Designed correctly, an ejector that operates in a transient system can provide entrainment for a finite period.

The performance model was not extended to include the mixing of the transient primary and secondary stream because the free expansion wave and the oblique shock wave could not be modelled accurately using one-dimensional theory. The results can be further improved by incorporating varied back pressure in the code as the blow down occurs. The back pressure is anticipated to increase during the blow down which will result in a reduced period of supersonic down stream flow.

8.   Acknowledgements

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