Review on Ejector Efficiencies in Various Ejector Systems

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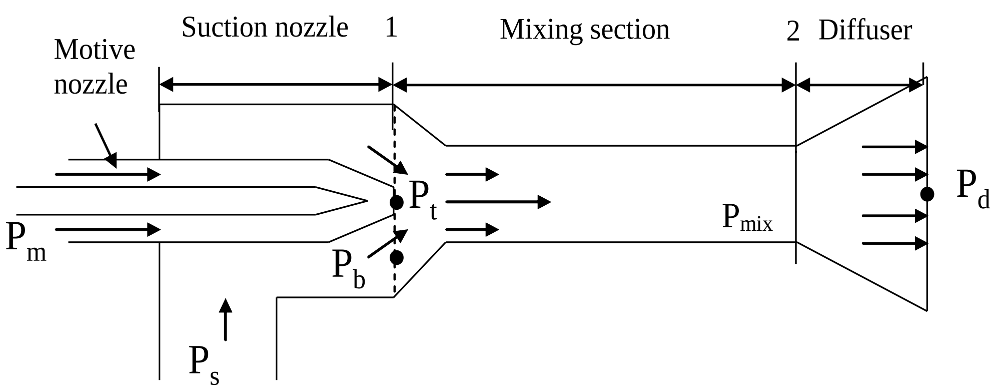
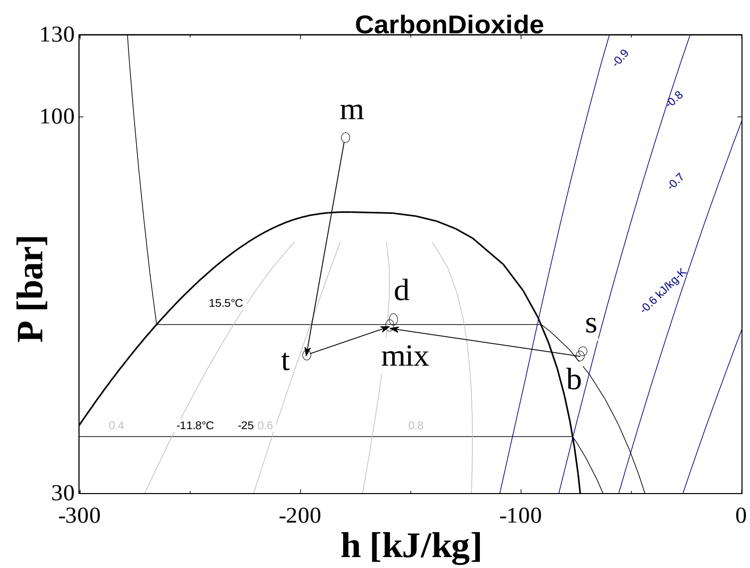
Introduction

- Ejector expansion device

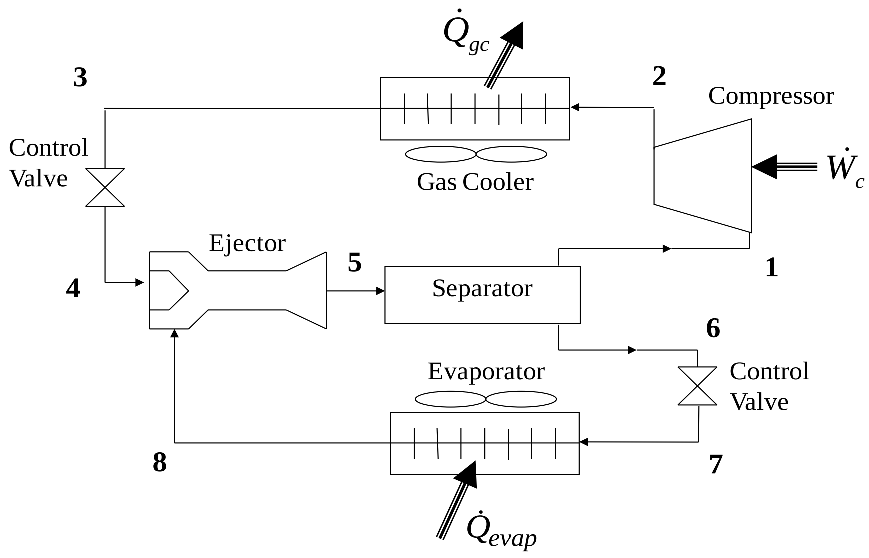
- Ejector working process



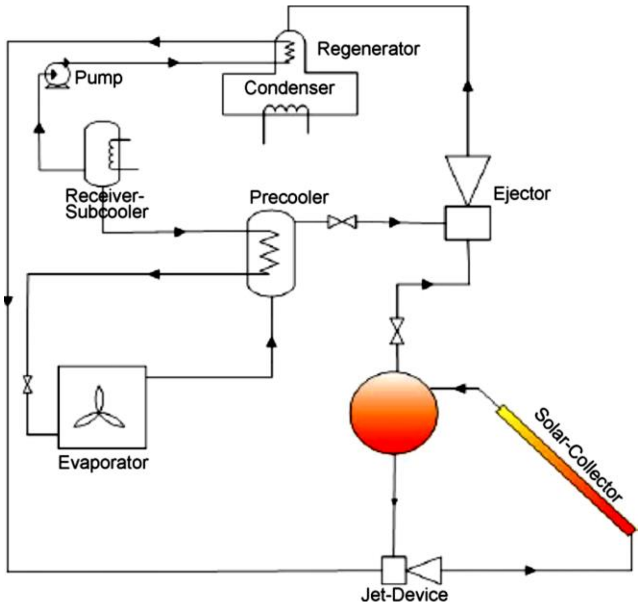


Introduction

- Application in refrigeration
  - » Recovery of expansion work
    - – vapor compression cycle
  - » Utilization of low-grade energy
    - – solar energy, geothermal energy and waste heat



Vapor compression ejector refrigeration system
(Liu and Groll 2008)



Solar-driven ejector refrigeration system
(Huang *et al*. 1998)

Overall ejector efficiency

- Definitions
  - » Definition (Elbel and Hrnjak, 2008)

$$\eta_{ejector} = \frac{\dot{W}_{rec}}{\dot{W}_{rec,max}} \quad (1)$$

  - » Expression (Köhler et al. 2007, Elbel and Hrnjak 2008)

$$\eta_{ejector} = \varphi \frac{(h'_{s,isen} - h_s)}{(h_m - h'_{m,isen})} \quad (2)$$

  - » Empirical equation (Lucas et al. 2013)

$$\eta_{ejector} = 0.43630 \left[\left(\frac{P_s \ln \frac{P_d}{P_s}}{P_m - P_d} \right)^{0.87843} \left(\frac{P_s}{P_m} \right)^{0.10313} \left(\frac{Oh_m}{Oh_s} \right)^{1.33917} \left(\frac{d_{mix} \rho_s}{d_t \rho_m} \right)^{-0.71533} \right] - 0.01770$$

(3)

Overall ejector efficiency

» Definition (Dvořák and Vit 2005, Butrymowicz et al. 2014)

$$\eta_{ejector} = \frac{\dot{m}_e}{\dot{m}_g} \frac{1-\left(\frac{P_e}{P_c}\right)^{\frac{k-1}{k}}}{\left(\frac{P_g}{P_c}\right)^{\frac{k-1}{k}}-1} \quad (4)$$

» Exergetic ejector efficiency (McGovern et al. 2012)

$$\eta_X = \varphi \frac{\ln(P_d/P_s)}{\ln(P_m/P_d)} \quad (5)$$

Overall ejector efficiency

- Variation of overall ejector efficiency
  - » Operating condition
  - » Ejector geometries
  - » Fluid properties

Authors	**Fluid**	**Ejector efficiency**	**Overall ejector efficiency**
Elbel and Hrnjak (2008)	CO2	Equation (1)	3.5% - 14.5% (Experiment)
Nakagawa *et al*. (2011)	CO2	Equation (1)	1 - 23% (experiment)
Lucas and Koehler (2012)	CO2	Equation (1)	7.8% - 21.5% (experiment)
Banasiak *et al*. (2012)	CO2	Equation (1)	23% - 31% (experiment)
Butrymowicz *et al*. (2014)	Isobutane	Equation (4)	8% - 16.5% (experiment)
Eames *et al* (1995)	Steam	Equation (5)	7.5% - 19.9% (experiment)
Bulusu *et al* (2008)	air	Equation (5)	1.0% - 5.3% (experiment)

Ejector component efficiencies

- Definitions
  - » Isentropic efficiency of motive nozzle

$$\eta_m = \frac{h_m - h_t}{h_m - h_{t,is}} \qquad (6)$$

  - » Isentropic efficiency of suction nozzle

$$\eta_s = \frac{h_s - h_b}{h_s - h_{b,is}} \qquad (7)$$

  - » Mixing efficiency
    - – Friction losses of mixing chamber (Huang 1999, Ksayer 2007, Liu and Groll 2008)

$$p_t A_t + \eta_{mix} \rho_t A_t V_t^2 + p_b \left(A_{mix} - A_t \right) + \eta_{mix} \rho_b \left(A_{mix} - A_t \right) V_b^2 = p_{mix} A_{mix} + \rho_{mix} A_{mix} V_{mix}^2 \qquad (8)$$

Ejector component efficiencies

– Manjili and Yavari 2012, Yu et al. 2007

$$\eta_{mix} = \frac{u'^2_{mix}}{u^2_{mix}} \qquad (9)$$

» Diffuser

– Ksayer (2007) , Li and Groll (2005)

$$\eta_d = \frac{h_{d,out,is} - h_{ms,out}}{h_{d,out} - h_{ms,out}} \qquad (10)$$

– Elbel and Hrnjak (2008)

$$\eta_d = \frac{\left(h_{d,out,is} - h_{ms,out}\right)}{\frac{1}{2} u^2_{ms,out}} \qquad (11)$$

Ejector component efficiencies

– Pressure recovery coefficient (Li 2006, Liu and Groll 2008)

$$Ct = \frac{p_d - p_{mix}}{\frac{1}{2}\rho_{mix} V_{mix}^2} \qquad (12)$$

– Correlation (Owen et al. 1992)

$$Ct = 0.85\rho_{mix}\left[1 - \left(\frac{A_{mix}}{A_d}\right)^2\right]\left[\frac{x_{mix}^2}{\rho_{g,mix}} + \frac{(1 - x_{mix})^2}{\rho_{f,mix}}\right] \qquad (13)$$

Ejector component efficiencies

- Assumed values in the literature

Authors	System Type	Fluid	η_m	η_s	η_{mix}	η_d
Keenan *et al*. (1950)	ejector	Air	1.0	1.0		
Alexis and Rogdakis (2003)	steam ejector refrigerator system	Water	0.7			0.8
Sun (1996)	powered by low-grade thermal energy	LiBr-H_2O/H_2O-NH_3	0.85	0.85		0.85
Vereda *et al*. (2012)	ejector-absorption refrigeration cycle	Ammonia/lithium nitrate	0.85	0.85	0.9	0.8
Domanski (1995)	compression cycle	-	0.85 - 0.9	0.85-0.9		0.7
Yapici and Ersoy (2005)	low grade waste heat in the vapor generator	R123	0.85	0.85		0.85
Yu and Li (2007)	conventional ejector refrigeration system	R141b	0.9		0.85	0.85
Yu *et al*. (2007)	regenerative ejector refrigeration cycle	R142b	0.85		0.95	0.85
Elbel and Hrnjak (2004)	vapor compression cycle	CO_2	0.9	0.9		0.9
Li and Groll (2005)	vapor compression cycle	CO_2	0.9	0.9		0.8
Ksayer and Clodic (2006)	vapor compression cycle	CO_2	0.85	0.85		0.75
Ksayer (2007)	vapor/liquid compression cycle	R141b	0.95	1.0	0.9-0.98	1
Deng *et al*. (2007)	vapor compression cycle	CO_2	0.7	0.7		0.8
Sarkar (2008)	vapor compression cycle	CO_2	0.8	0.8		0.75
Elbel and Hrnjak (2008)	vapor compression cycle	CO_2	0.8	0.8		0.8
Sun and Ma (2011)	vapor compression cycle	CO_2	0.9	0.9		0.8
Manjili and Yavari (2012)	vapor compression cycle	CO_2	0.7	0.7	0.95	0.8

Ejector component efficiencies

- Determination Methods
  - » CFD modeling (Varga et al. 2009, steam)
    - – Motive nozzle efficiency: constant
    - – Efficiencies of suction, mixing and diffuser sections depend on operating conditions
  - » Based on experimental results (Ksayer, 2007)
    - – Mixing efficiency (R141b)

$$\eta_{mix} = -0.0113(D_{mix}/D_t)^2 + 1.0501 \quad (14)$$

    - – Range: 0.90 – 0.98

Ejector component efficiencies

- » Based on ejector modeling and measured data (Liu and Groll, 2008)
  - – Ejector component efficiencies (CO_2)
    - Motive nozzle efficiency: $0.50 \leq \eta_m \leq 0.93$
    - Suction nozzle efficiency: $0.37 < \eta_s < 0.90$
    - Mixing efficiency: $0.50 < \eta_{mix} < 1.00$
  - – Boundaries
    - 8.0 MPa < P_m <14.0 MPa, 2.5 MPa < P_s <5.0 MPa
    - 40 °C < T_m < 60 °C, 15 °C < T_s < 26 °C
    - 0.1 g/s < $\dot{m}_m$ < 0.25 g/s, 0.05 g/s < $\dot{m}_s$ < 0.07 g/s
    - 1.8 mm < D_t <2.7 mm, D_{mix} = 4 mm

Ejector component efficiencies

– Motive nozzle efficiency

$$\eta_m = -36.137 - 4.160\left(\frac{P_m}{P_s}\right) + 1.161\left(\frac{P_m}{P_s}\right)^2 - 0.106\left(\frac{P_m}{P_s}\right)^3 + 212.320\left(\frac{D_t}{D_{mix}}\right) - 355.359\left(\frac{D_t}{D_{mix}}\right)^2 + 196.035\left(\frac{D_t}{D_{mix}}\right)^3 \quad (15)$$

– Suction nozzle efficiency

$$\eta_s = -3173.171 + 934.102\left(\frac{P_m}{P_s}\right) - 314.471\left(\frac{P_m}{P_s}\right)^2 + 79.521\left(\frac{P_m}{P_s}\right)^3 - 12.222\left(\frac{P_m}{P_s}\right)^4$$

$$+0.814\left(\frac{P_m}{P_s}\right)^5 + 694222.1\varphi - 2956145\varphi^2 + 7950453\varphi^3 - 114327270\varphi^4 + 6689155\varphi^5$$

$$-649905.1Z + 2647000Z^2 - 6885025Z^3 + 9627161Z^4 - 5490126Z^5 \left(Z = \varphi\left(\frac{P_m}{P_s}\right)^{0.02}\right) \quad (16)$$

– Mixing efficiency

$$\eta_{mix} = -6869.077 + 19308.18Z' - 18089.31Z'^2 + 5649.417Z'^3 \qquad Z' = \left(\frac{D_t}{D_{mix}}\right)^{0.1}(1+\varphi)^{0.35} \quad (17)$$

Summary and Discussions

- Overall ejector efficiency
- Ejector component efficiencies
- Further efforts
  - » Improve methods of determining actual ejector component efficiencies
  - » Study on effects of operating conditions, ejector geometries and working fluid characteristics on ejector component efficiencies