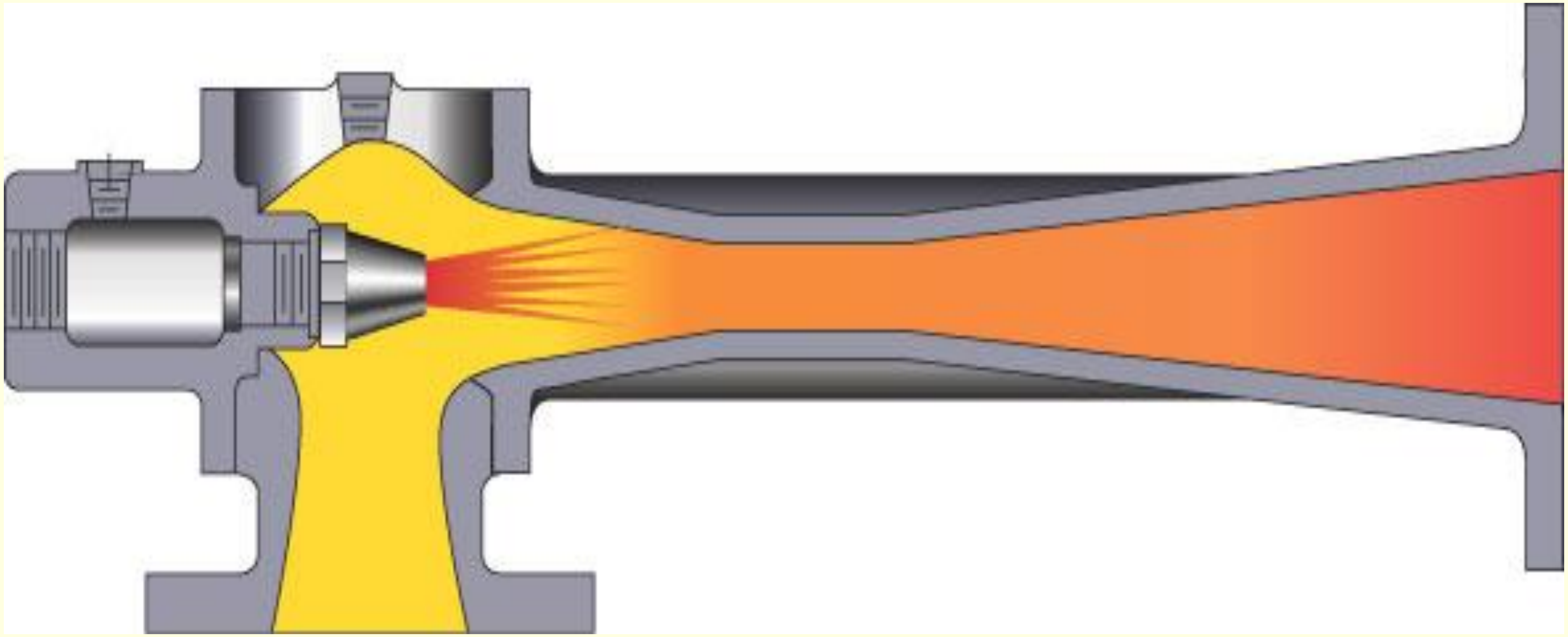
Optimization of a high-efficiency jet ejector by using computational fluid dynamic (CFD) software



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1. Introduction

1.1 Jet ejector advantages and applications

1.2 List of parameters

- flow parameters
- geometric parameters

1.3 Operating principle

1.4 Jet ejector types

- constant-pressure jet ejector
- constant-area jet ejector

1.5 High-efficiency jet ejector

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1.1 Jet ejector advantages

Jet ejector advantages

- easy maintenance, because no moving parts
- low capital cost
- easily installed

Jet ejector disadvantage

- low efficiency device

www.artisanind.com

1.1 Jet ejector applications

Jet ejector applications

- vacuum distillation
- evaporation
- drying
- filtration
- desalination

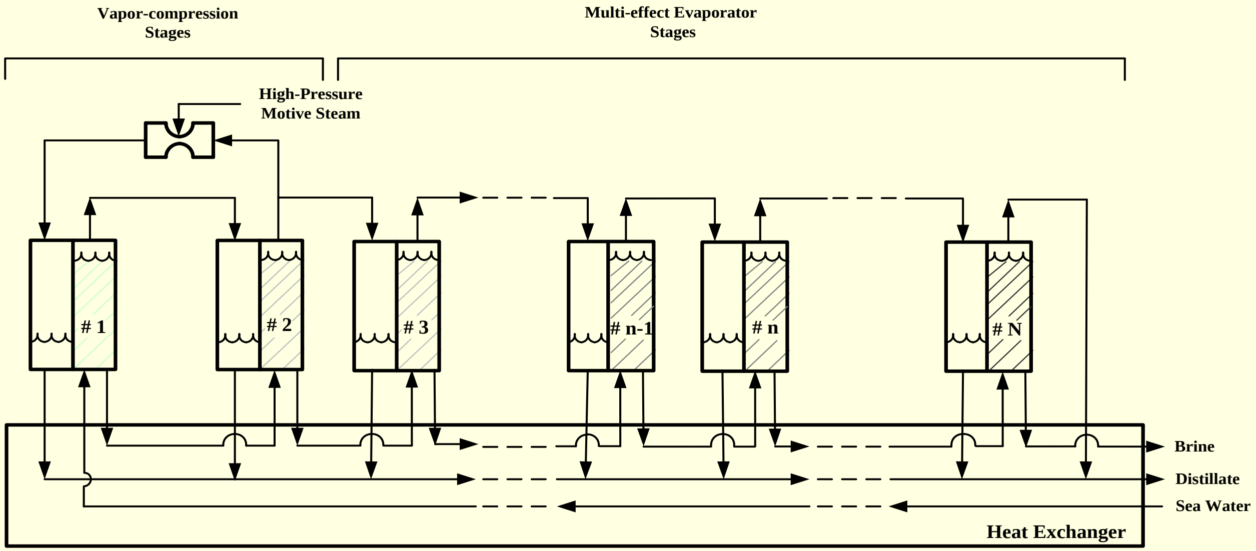
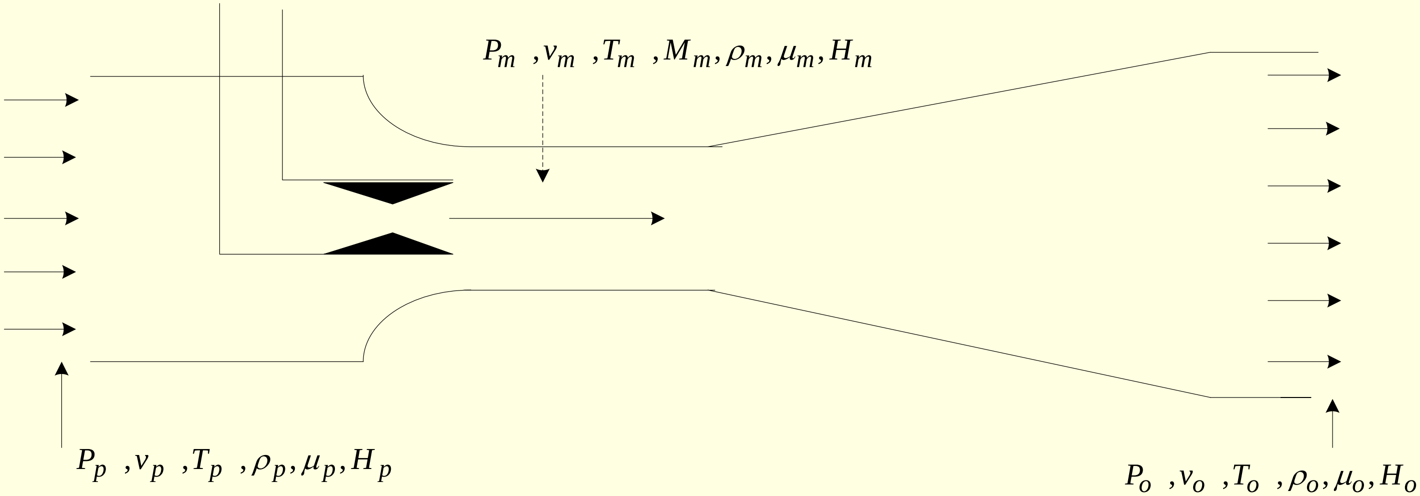


Diagram showing a jet ejector implemented in a desalination process

1.2 List of parameters

Flow parameters

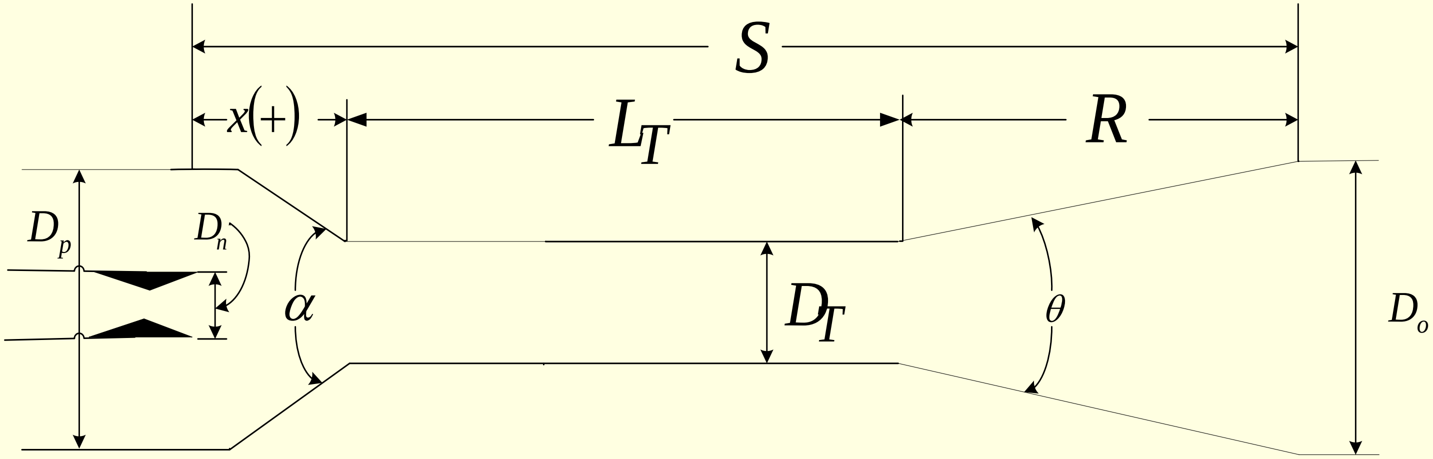


$$\textbf{Compression ratio} = \frac{P_o}{P_p}$$

$$\textbf{Entrianment ratio} = \textbf{Mass flow ratio} = \frac{M_m}{M_p}$$

1.2 List of parameters

Geometric parameters

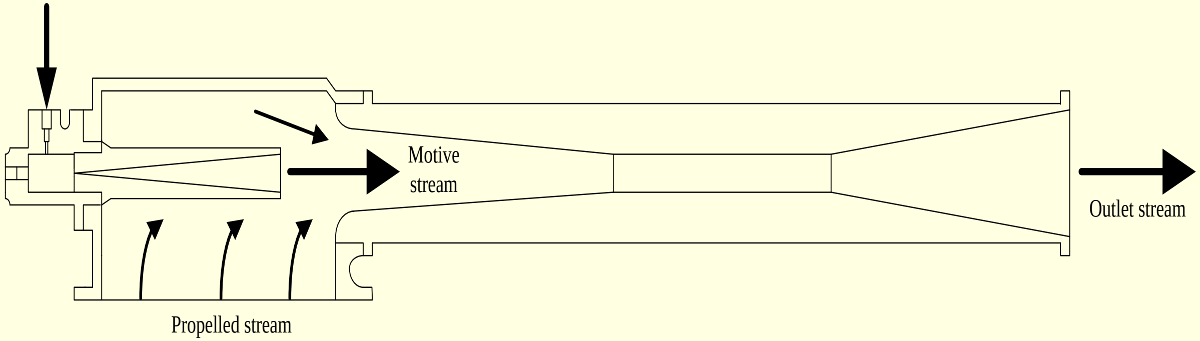


Dimensionless geometric parameters

$$\frac{L_T}{D_p},\frac{D_T}{D_p},\frac{D_n}{D_p},\qquad \frac{D_o}{D_p}=1$$

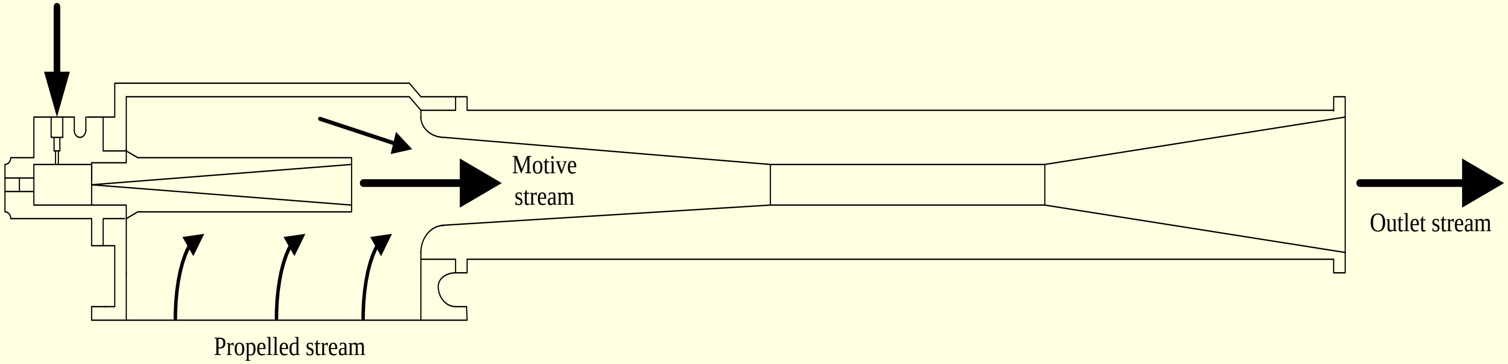
1.3 Operating principle

Energy of Motive Stream → Kinetic Energy → **Energy of propelled Stream**

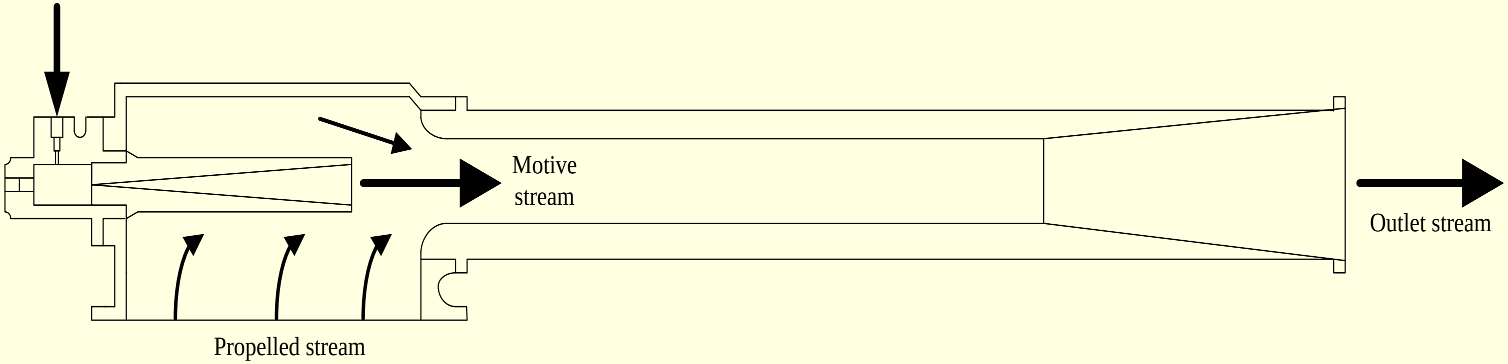


1.4 Jet ejector types

Constant-pressure (conventional) jet ejector



Constant-area jet ejector



1.5 High-efficiency jet ejector

The key idea

Minimize the velocity difference between motive and propelled stream

1.5 High-efficiency jet ejector

Mathematical verification
of
the key idea

1.5 High-efficiency jet ejector

Conventional jet ejector

- large different velocitites

$M_m = 1.0$ kg/s $\quad v_m = 10$ m/s

$M_p = 1.0$ kg/s $\quad v_p = 1$ m/s

$M_{mix} = 2.0$ kg/s

$v_{mixture} = 5.5$ m/s

Kinetic energy

$(E_k)_m = 50$ J/s

$(E_k)_p = 0.5$ J/s

Kinetic energy

$(E_k)_{mixture} = 27.5$ J/s

$$\eta = \frac{(E_k)_{mixture}}{(E_k)_p + (E_k)_m} = \frac{27.5 \ \mathrm{J}/\mathrm{s}}{0.5 \ \mathrm{J}/s + 50 \ \mathrm{J}/s}$$

$$\eta = 0.545$$

1.5 High-efficiency jet ejector

High-efficiency jet ejector

- small different velocitites

$M_m = 1.0 \text{ kg/s}$ $v_m = 10 \text{ m/s}$

$M_p = 1.0 \text{ kg/s}$ $v_p = 6 \text{ m/s}$

$M_{mix} = 2.0 \text{ kg/s}$

$v_{mixture} = 8 \text{ m/s}$

Kinetic energy

$$(E_k)_m = 50 \text{ J/s}$$

$$(E_k)_p = 18 \text{ J/s}$$

Kinetic energy

$$(E_k)_{mixture} = 64 \text{ J/s}$$

$$\eta = \frac{(E_k)_{mixture}}{(E_k)_p + (E_k)_m} = \frac{64 \ \text{J}/\text{s}}{18 \ \text{J}/\text{s} + 50 \ \text{J}/\text{s}}$$

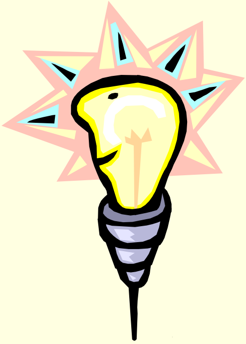
$$\eta = 0.941$$

1.5 High-efficiency jet ejector

Implement the key idea

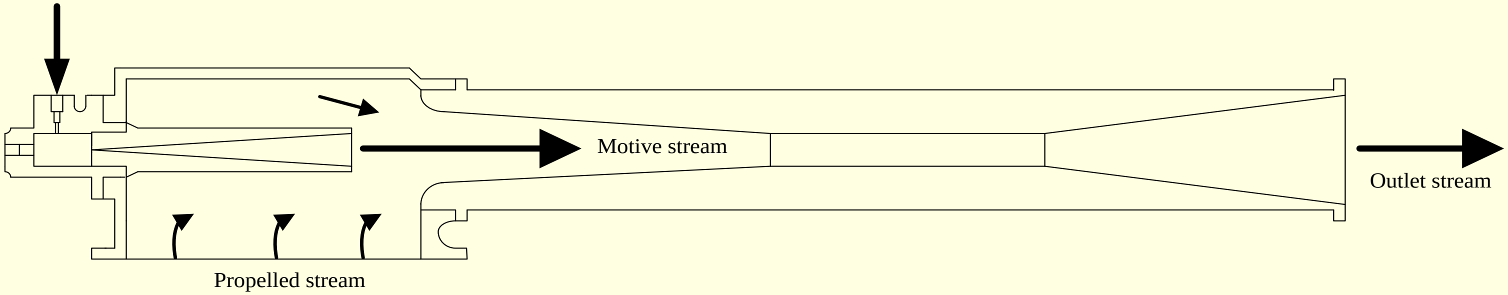
for

a high-efficiency jet ejector

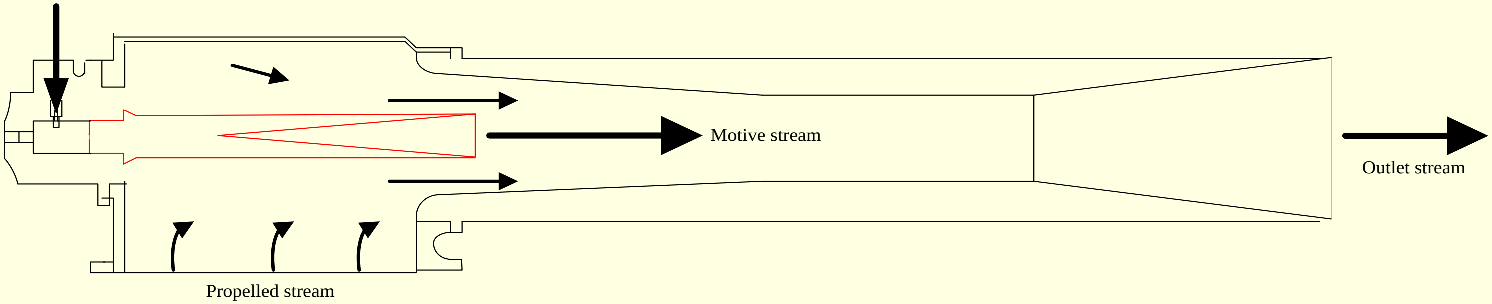


1.5 High-efficiency jet ejector

Conventional jet ejector



High-efficiency jet ejector



2. Research motivation

There are 3 reasons why this research is needed.

2. Research motivation

1. The results of the optimum geometry summarized by Kroll are not consistent; therefore, it is hard to rely on them.

Reference	Length of				Angle of Diffuser (degree)	
Air-Jet Air Pumps	Throat	Divergence	Nozzle Outlet to Discharge	Nozzle Outlet to Throat	Convergence	Divergence
symbol	$\boldsymbol{L_T}$	$\boldsymbol{R}$	$\boldsymbol{S}$	$\boldsymbol{X}$	$\boldsymbol{\alpha}$	$\boldsymbol{\theta}$
Keenan and Neumann (1942)	7 D_T	-	7.5 D_T	0.5 D_T	well rounded	-
Mellanby (1928)	4 D_T	10 D_T	-	variable	25	12
Kravath (1940)	1 D_T	12 D_T	15 D_T	2 D_T	28	5
Miller (1940)	-	-	-	5 D_T	-	16
Steam-Jet Air Pumps						
DuPerow and Bossart (1927)	-	-	6 D_T	1.2 D_T	-	7
Royds and Johnson (1941)	10 D_T	15 D_T	-	-	well rounded	-
Langhaar (1946)	3 D_T	4 D_T	10 D_T	3	24	10
Watson (1933)	2 D_T	6.7 D_T	12.3 D_T	3.6 D_T	28	8

summary of literature results about the optimization of the jet ejector (Kroll, 1947).

2. Research motivation

2. A well-know chart for designing a jet ejector (DeFrate and Hoerl (1959)):

- Limited compression ratio (1 to 10)
  - In my research, compression ratio (1 to 60)
- Poor description of optimal geometry

D_T/D_n ✓

Optimum D_n ✗

D_n/D_p ✗

D_T/D_p ✗

L_T ✗

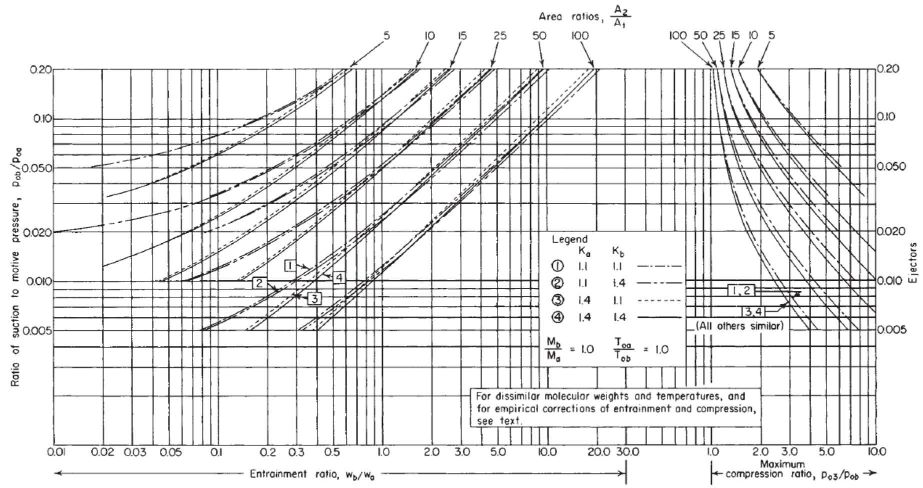


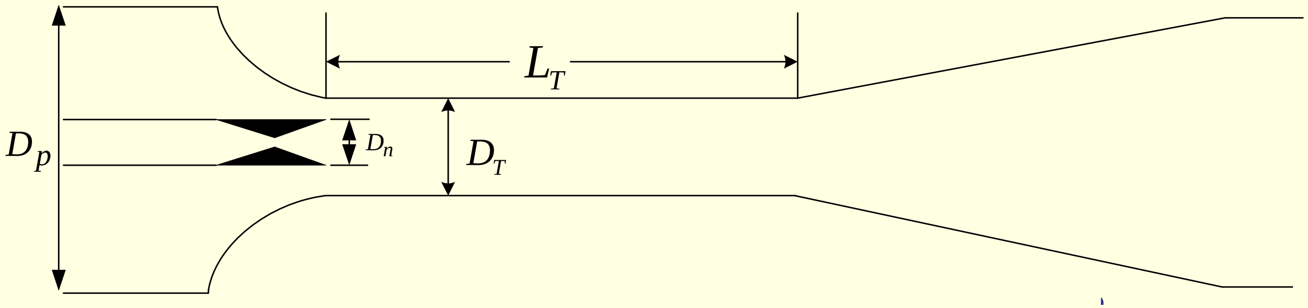
FIG. 10-102 Design curves for optimum single-stage ejectors. [*DeFrate and Hoerl,* Chem. Eng. Prog., **55**, *Symp. Ser. 21, 46 (1959).*]

Design curves for optimum single-stage ejectors (DeFrate and Hoerl, 1959). source: Perry's chemical engineering handbook; 7th edition, pg. 10-57

2. Research motivation

3. Few literature studies on the effect of nozzle diameter on jet ejector performance.

In my research, an optimum nozzle diameter (D_n) is investigated as the function of motive velocity (170 to 1104 m/s).



3. Verify CFD software

Computational fluid dynamic (CFD) software: Gambit & Fluent 2D

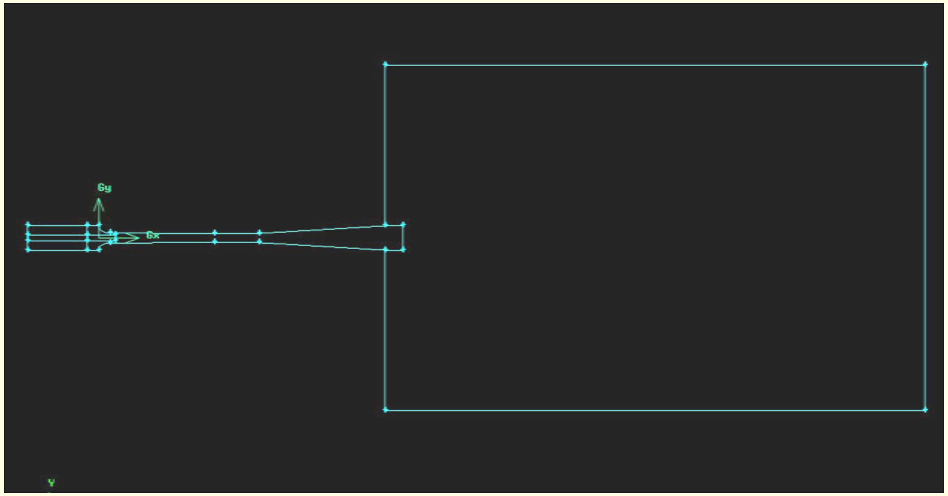
Procedure:

Generate a 2-dimension axi-symetric jet ejector geometry in the Gambit and asking them simulate fluid flow inside the geometry by using the Fluent 2d. Fluent 2D uses a mass-average segregated solver to solve the fundamental transport equations such as continuity, momentum conservation, and momentum conservation for compressible, Newtonian fluid (the Navier-Stokes equation).

It is a crucial step to verify the software reliability before applying it in the research.

3. Verify CFD software

Questions on the CFD software?



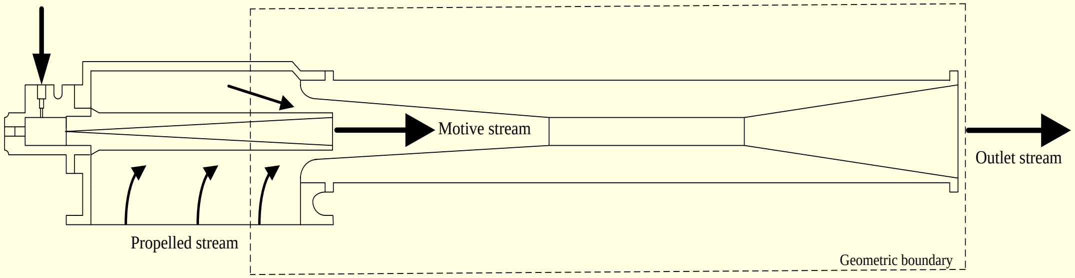
1. Which boundary condition should be applied in model?

2. What is an optimum number of grid elements?

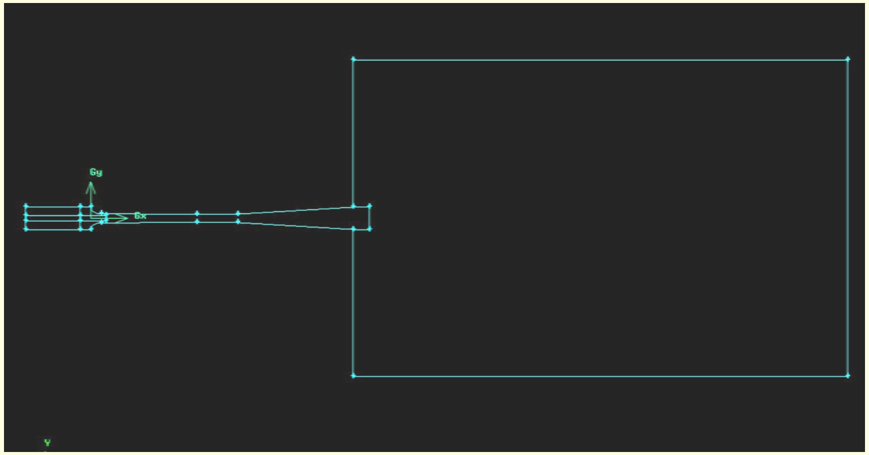
   The number of grid elements affects the result quality.

3. What is an optimum number of iterations?

   The number of iterations affects the result convergence.



3.1 Software boundary condition



1. Which boundary condition should be applied in model?

There are 2 boundary conditions available:

1. Total pressure:

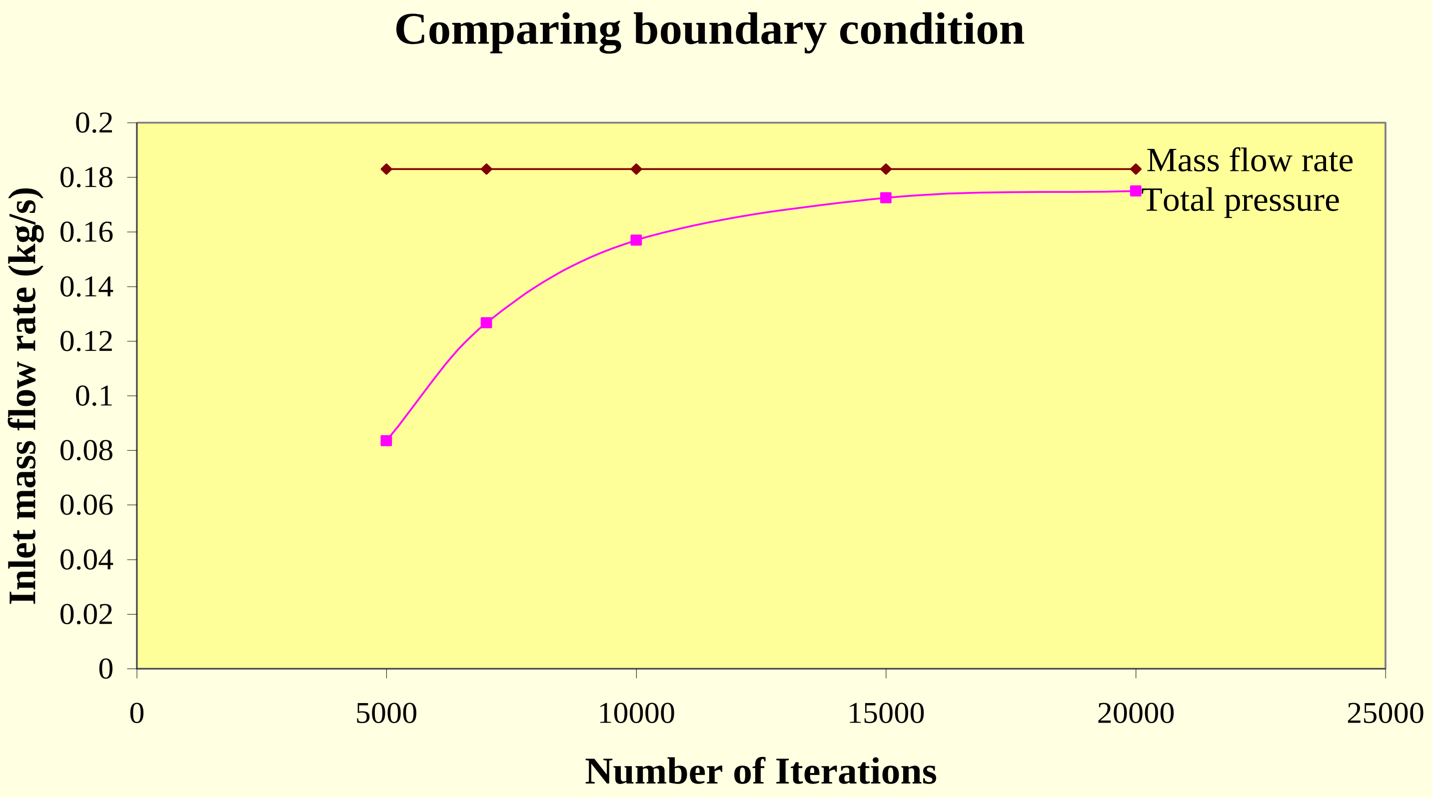
    work better at static condition

2. Mass flow rate:

    work better at dynamic condition

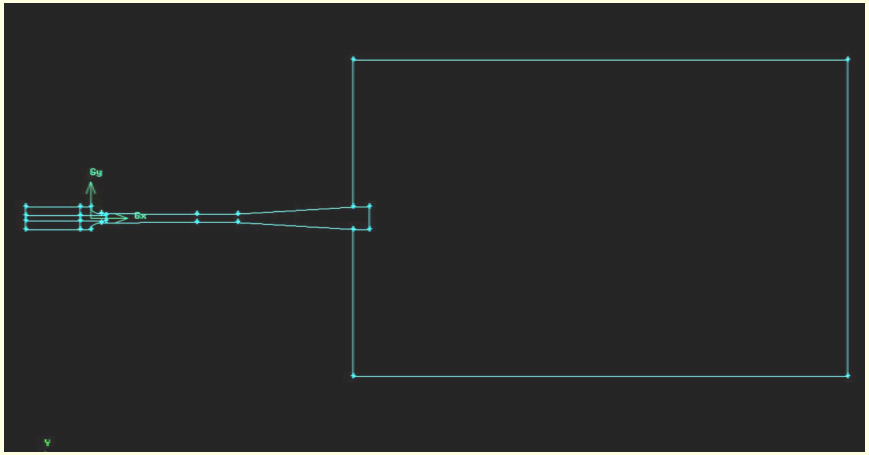
Available boundary condition in the software		
Model position		
Propelled stream inlet ????	Motive stream inlet	Box at the jet ejector outlet
Total pressure	Total pressure	Total pressure
Mass flow rate	Mass flow rate	Mass flow rate

3.1 Software boundary condition



Both boundary conditions are approaching the same result, but the total pressure boundary condition requires much larger number of iterations. As a consequence, it requires much more time consumption and memory resources.

3.1 Software boundary condition



The mass flow rate boundary condition gives convergence more quickly than the total pressure boundary condition; therefore, the mass flow rate boundary condition was used for the propelled stream inlet boundary condition in the research.

Available boundary condition in the software		
Model position		
Propelled stream inlet	Motive stream inlet	Box at the jet ejector outlet
Total pressure	Total pressure	Total pressure
Mass flow rate	Mass flow rate	Mass flow rate

3.2 Number of grid elements and iterations

An optimum number of grid elements and iterations

1. An optimum number of grid elements :

the more grid elements, the better result quality is. But it will consume an enormous time and memory space.

2. Number of iterations:

The number of iterations affects the result convergence. After a particular iterations, the result will not change a lot because it has already converged.

“It is worth to investigate an optimum number of grid elements and iterations to obtain simulation results as fast as possible, but still maintain high quality.”

3.2 Number of grid elements and iterations

Coarser grid*

Number of iterations	Pressure (Pa)			Efficiency	Compression Ratio	(h) Time consumed
	Motive	Inlet	Outlet			
2500	97842	98124	101326	**0.978**	**1.033**	**2**
4500	97785	98031	101325	**0.978**	**1.034**	**3**
6000	97785	98031	101325	**0.978**	**1.034**	**4**

Finer grid*

Number of iterations	Pressure (Pa)			**Efficiency**	**Compression ratio**	**(h) Time consumed**
	Motive	Inlet	Outlet			
2500	97793	98061	101325	**0.978**	**1.033**	**5**
4500	97764	98008	101327	**0.979**	**1.034**	**7**
6000	97762	98003	101327	**0.979**	**1.034**	**10**

* The experiment was included the effect of compressible fluid

3.3 Verify software accuracy

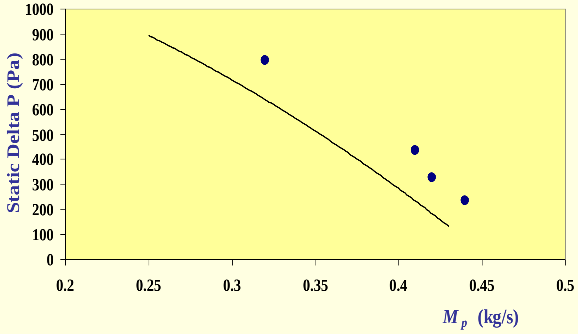
Software accuracy

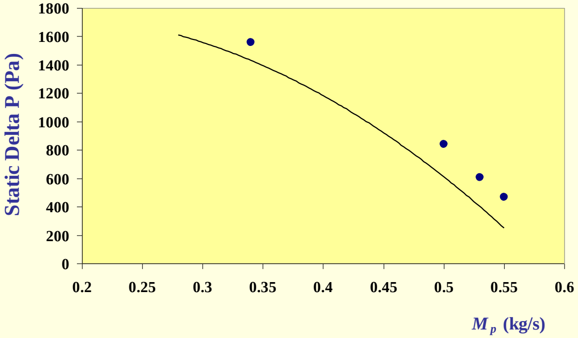
Simulation results was compared with experiment results.

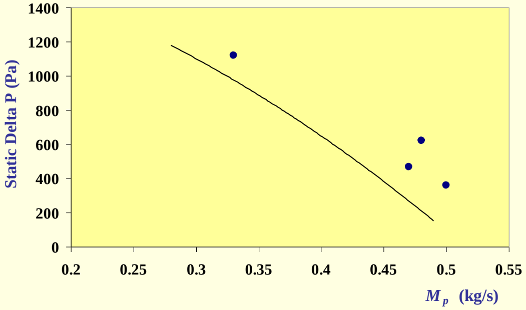
The jet ejector geometry in the model is exactly the same as in experimental apparatuses.

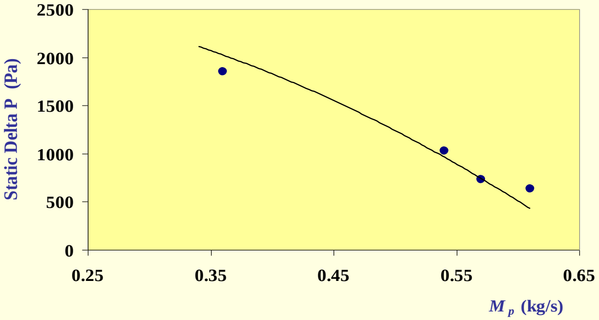
Air is used as a working fluid for motive and propelled stream at various motive velocity (411 to 563 m/s)

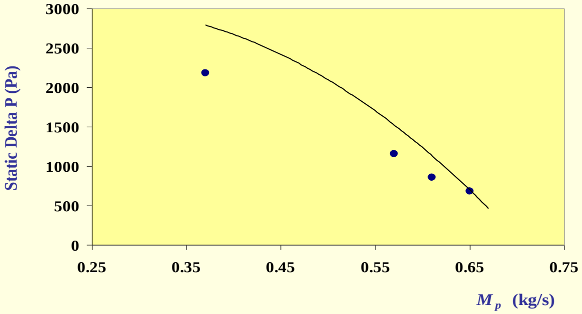
3.3 Verify software accuracy

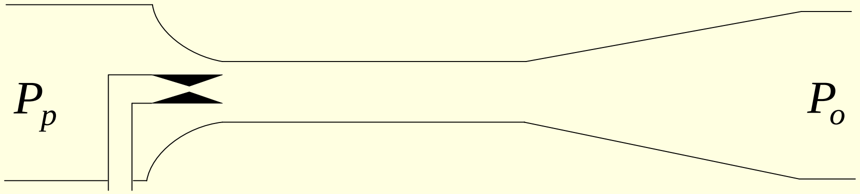

Motive velocity = 411 m/s


Motive velocity = 490 m/s


Motive velocity = 448 m/s


Motive velocity = 527 m/s


Motive velocity = 562 m/s



3.3 Verify software accuracy

The simulation results obtained directly from the first-principle model (no adjustable parameters required).

The simulation results lie approximately on the experiment results in every case. The average overall deviation between the simulation and experiment results is 8.19%

Things obtained from this stage:

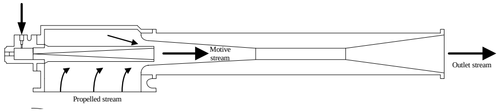
- The proper model boundary condition
- An optimum number of grid elements (coarser grid size)
- An optimum number of iterations (2,500 iterations)
- Software can provide satisfactory results and highly accuracy.

4. Optimization jet ejector

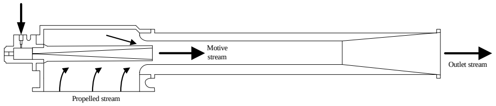
The jet ejector optimization procedure:

Verifying the better design

Constant-pressure jet ejector



Constant-area jet ejector

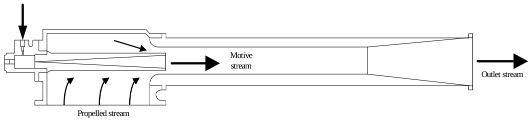


Step 1

Optimizing the better design between both geometries

Step 2

Optimizing alternative strategies to add motive stream

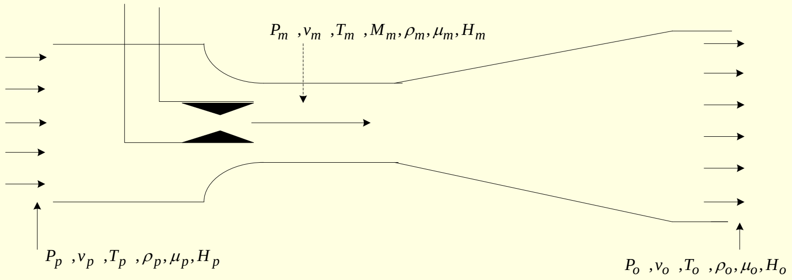


Step 3

4. Optimization jet ejector

Conventional efficiency equation:

$$\eta = \frac{M_p\left(H_o - H_p\right)}{M_m\left(H_m - H_o\right)}$$



Why a new efficiency equation has to be derived?

1. A conventional efficiency equation does not account for the kinetic energy term, which is incorrect.

2. A conventional efficiency equation does not interface with CFD software.

4. Optimization jet ejector

New-derived efficiency equation:

Energy components

Kinetic energy

$$\dot{E}_k = \frac{1}{2}\dot{m}v^2$$

Pressure energy

$$\dot{E}_p = \dot{m}\left(\frac{\gamma-1}{\gamma}\right)RT\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma}{\gamma-1}} - 1\right]$$

Flow work

$$F_w = P\hat{V}$$

4. Optimization jet ejector

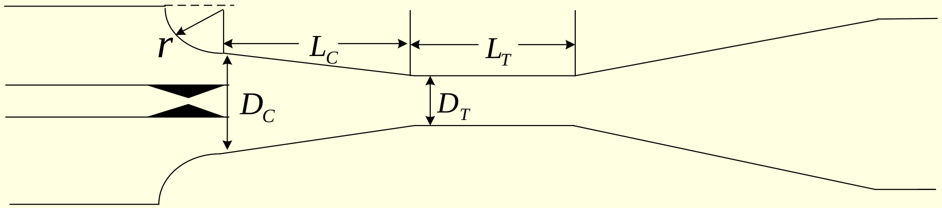
New-derived efficiency equation

$$\eta = \frac{\overset{\text{Kinetic energy}}{\overleftrightarrow{\frac{1}{2} M_o v_o^2}} + \overset{\text{Flow work}}{\overleftrightarrow{M_p \frac{RT_p}{MW} + M_m \frac{RT_m}{MW}}} + \overset{\text{Pressure energy}}{\overleftrightarrow{M_p \left(\frac{\gamma}{\gamma - 1}\right) \frac{RT_p}{MW} \left[\left(\frac{P_o}{P_p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] + M_m \left(\frac{\gamma}{\gamma - 1}\right) \frac{RT_m}{MW} \left[\left(\frac{P_o}{P_m}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}}}{\underset{\text{Kinetic energy}}{\overleftrightarrow{\frac{1}{2} M_p v_p^2 + \frac{1}{2} M_m v_m^2}} + \underset{\text{Flow work}}{\overleftrightarrow{M_p \frac{RT_p}{MW} + M_m \frac{RT_m}{MW}}}}$$

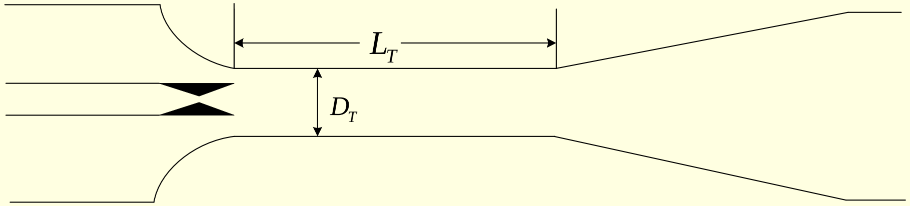
4.1 Constant-pressure vs. constant-area

Optimized parameters:

A constant-pressure jet ejector



A constant-area jet ejector



Nozzle diameter ratio is not included in this study. The nozzle diameter ratio is specified at 0.029

Optimization conditions:

Steam using as a working fluid for both propelled and motive stream.

Motive velocity from 170 to 850 m/s

Mass flow ratio from 0.023 to 100

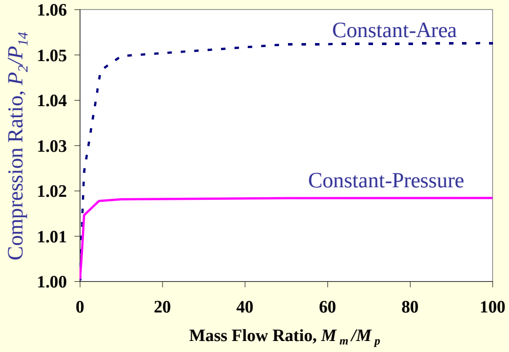
Nozzle is placed at the beginning of the throat section ($x = 0$; ESDU recommendation).

Exit pressure = 1 atm.

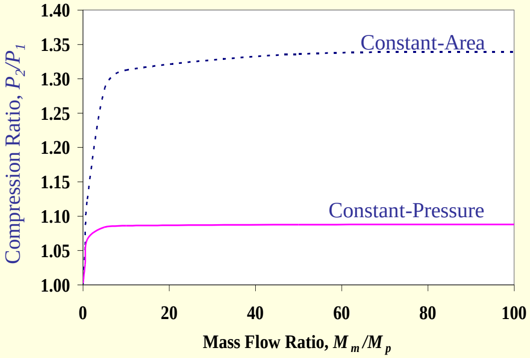
4.1 Constant-pressure vs. constant-area

Compression ratio

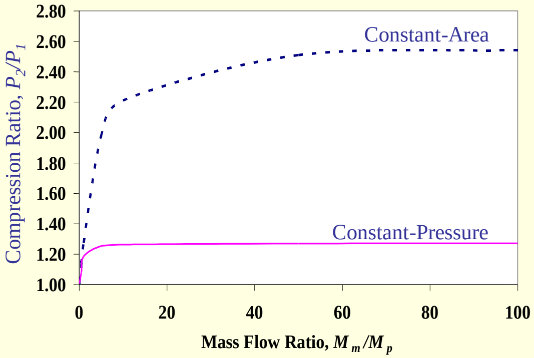
V_m = 170 m/s



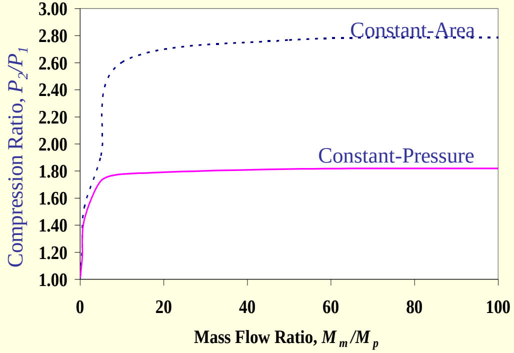
V_m = 340 m/s



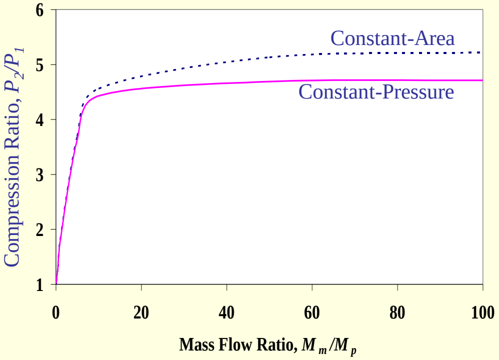
V_m = 510 m/s

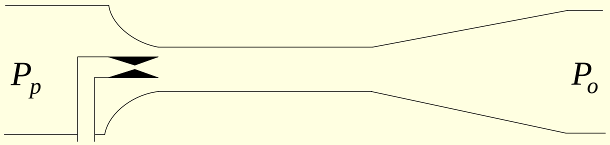


V_m = 680 m/s



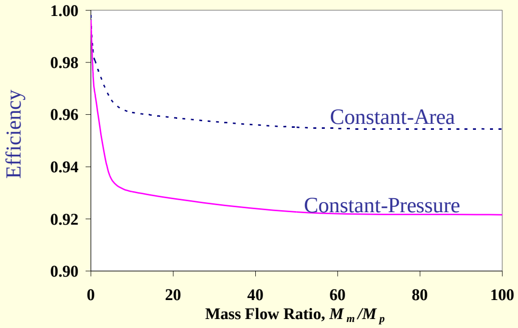
V_m = 850 m/s

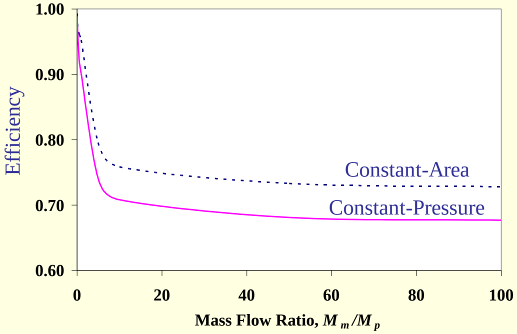


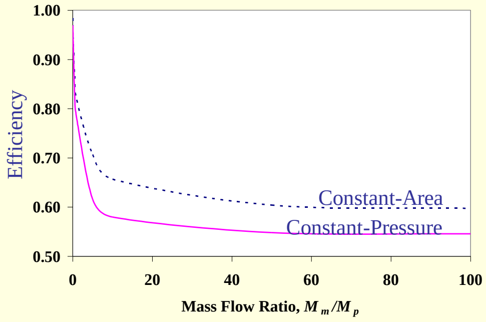


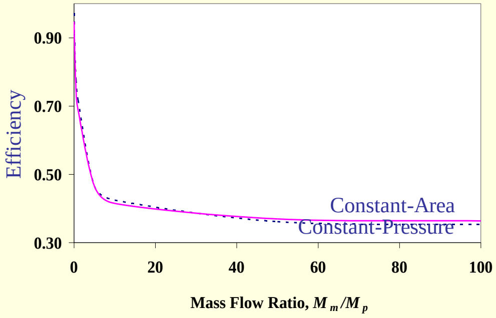
4.1 Constant-pressure vs. constant-area

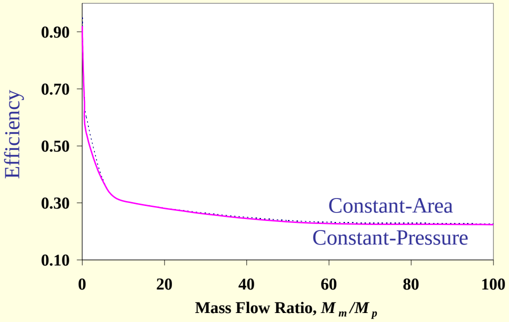
Efficiency


V_m = 170 m/s


V_m = 340 m/s

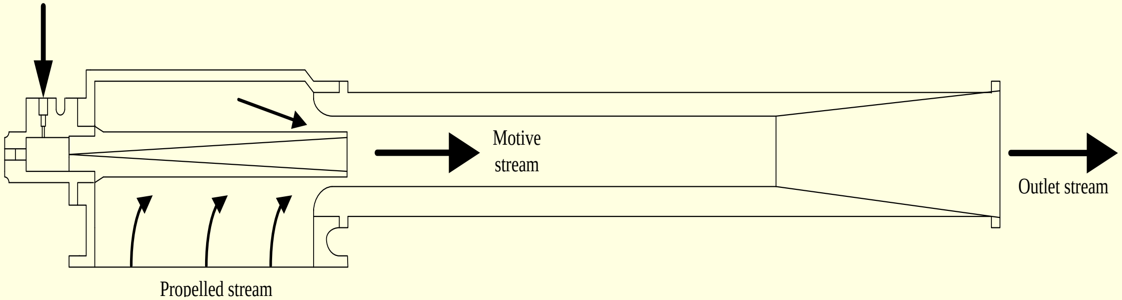

V_m = 510 m/s


V_m = 680 m/s


V_m = 850 m/s

4.1 Constant-pressure vs. constant-area

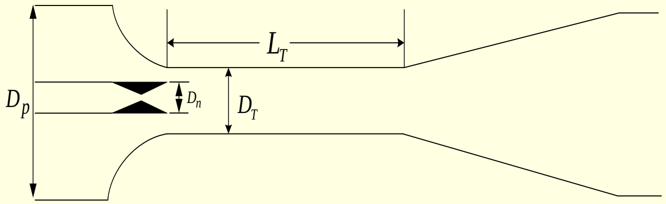
The constant-area jet ejector produce higher performance (compression ratio and efficiency) for all motive velocity and mass flow ratio; therefore, it was selected to study in the next stage (optimization stage). The advantage is more pronounce at low motive velocity.



4.2 Optimization constant-area jet ejector

Optimized geometric parameters:

Throat length ratio (L_T/D_p), throat diameter ratio (D_T/Dp) ,and nozzle diameter ratio (0.01 to 0.05; D_n/Dp)



Independent parameters:

Motive velocity (170 to 1104* m/s; V_m),

mass flow ratio (0.01 to 100; M_m/M_p)

Dependent parameters:

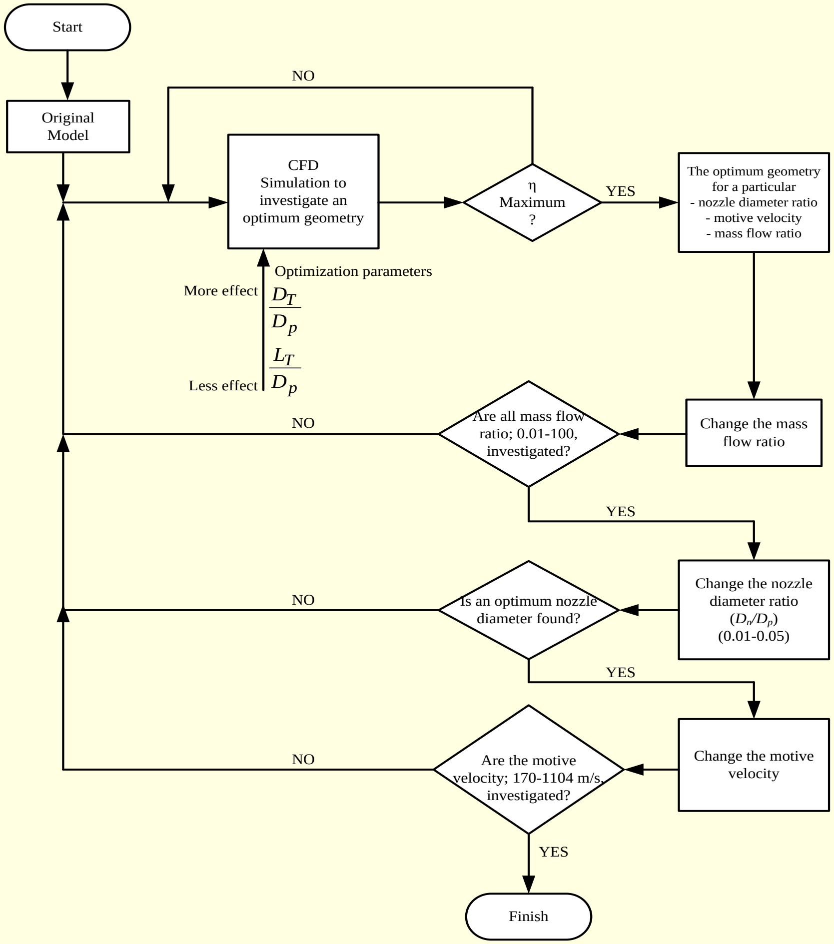
Compression ratio (P_o/P_p), efficiency (η)

(Exit pressure = 1 atm.)

*According to the literature (Lines and Smith, 1997), the conventional operating motive velocity is between 900 and 1200 m/s. Numerical problem prevents investigation above 1104m/s.

4.2 Optimization constant-area jet ejector

Optimization procedure



Start

Original Model

CFD Simulation to investigate an optimum geometry

η Maximum ?

NO

YES

The optimum geometry for a particular
- nozzle diameter ratio
- motive velocity
- mass flow ratio

Optimization parameters

More effect

$\frac{D_T}{D_p}$

$\frac{L_T}{D_p}$

Less effect

Change the mass flow ratio

Are all mass flow ratio; 0.01-100, investigated?

NO

YES

Change the nozzle diameter ratio (D_n/D_p) (0.01-0.05)

Is an optimum nozzle diameter found?

NO

YES

Change the motive velocity

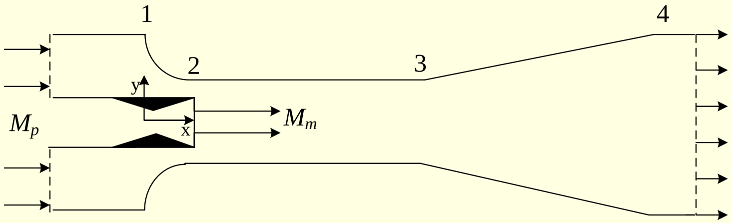
Are the motive velocity; 170-1104 m/s, investigated?

NO

YES

Finish

Original model

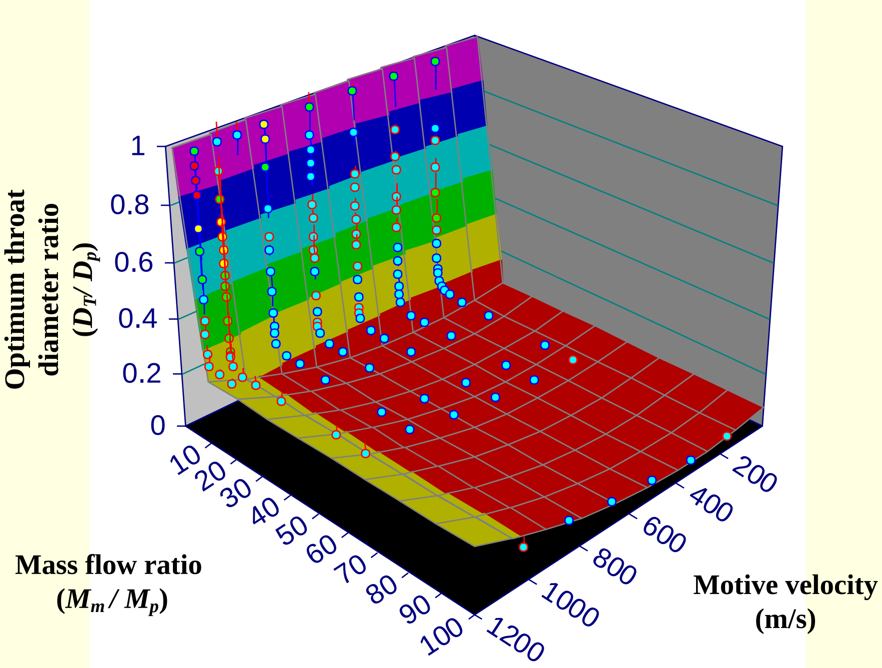


Point number	x-coordinate	y-coordinate
1	0	105.7783
2	97.79	39.8653
3	1,367.79	39.8653
4	2,442.21	105.7783

4.2 Optimization constant-area jet ejector

Optimized geometric parameter results

Optimum throat diameter ratio (D_T/D_p)



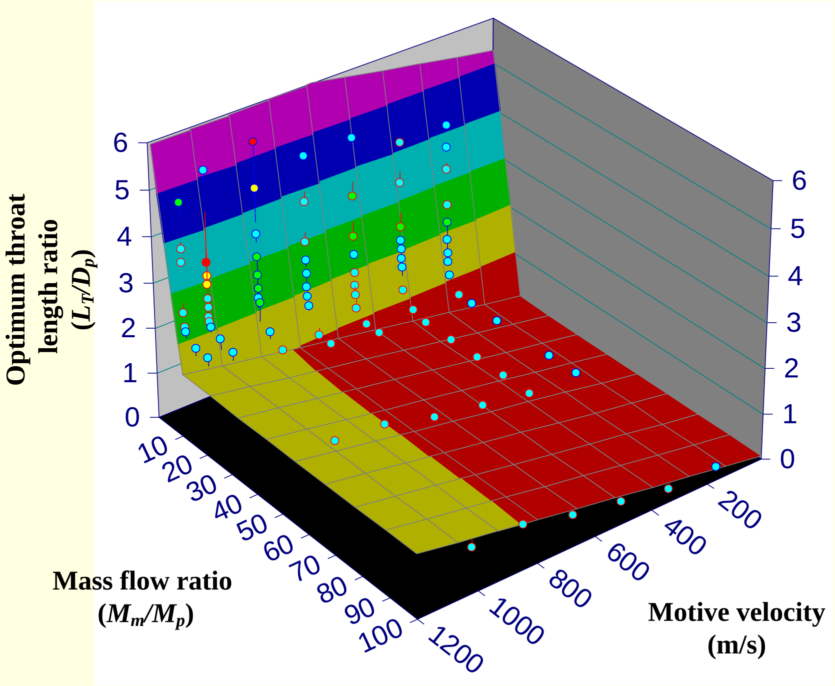
Optimum throat diameter ratio increases as function of motive velocity and inverse function of mass flow ratio.

The optimum throat diameter ratio increases dramatically when the mass flow ratio is lower than 5.0 for all motive velocity.

4.2 Optimization constant-area jet ejector

Optimized geometric parameter results

Optimum throat length ratio (L_T/D_p)



Optimum throat length ratio increases as function of motive velocity and inverse function of mass flow ratio.

The optimum throat length ratio increases dramatically when the mass flow ratio is lower than 5.0 for all motive velocity.

4.2 Optimization constant-area jet ejector

Optimized geometric parameter results

Optimum nozzle diameter ratio (D_n/D_p)

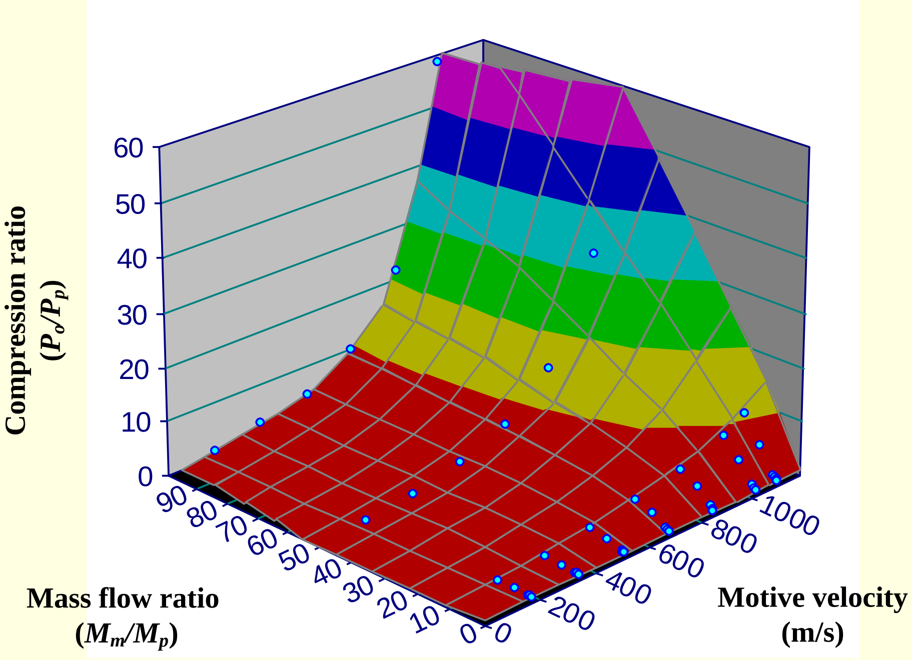
Motive velocity (m/s; V_m)	Optimum nozzle diameter ratio (D_n/D_p)
170	0.050
340	0.046
510	0.044
680	0.044
850	0.044
1020	0.030
1104	0.030

The optimum nozzle diameter ratio decreases at higher motive velocity.

4.2 Optimization constant-area jet ejector

Dependent parameter results

Compression ratio (P_o/P_p)



Compression ratio increases when motive velocity increases and mass flow ratio increases.

The compression ratio does not increase much at low motive velocity (< 850 m/s), but it increases drastically at high motive velocity (> 850 m/s).

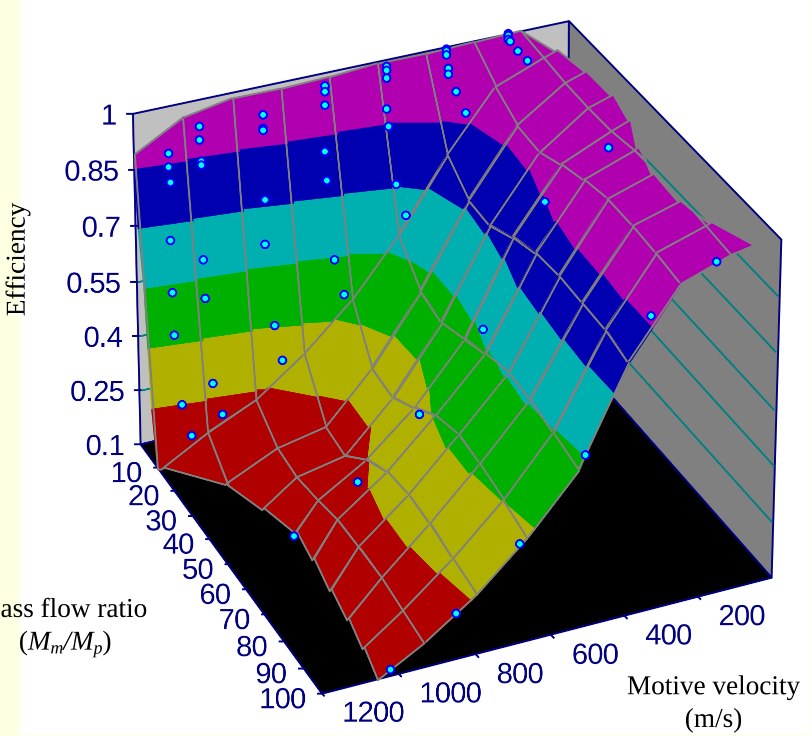
For every motive velocity, the compression ratio starts increasing significantly at the mass flow ratio higher than 1.0

The maximum compression ratio is 58.45 at motive velocity 1020 m/s and mass flow ratio 100.

4.2 Optimization constant-area jet ejector

Dependent parameter results

Efficiency



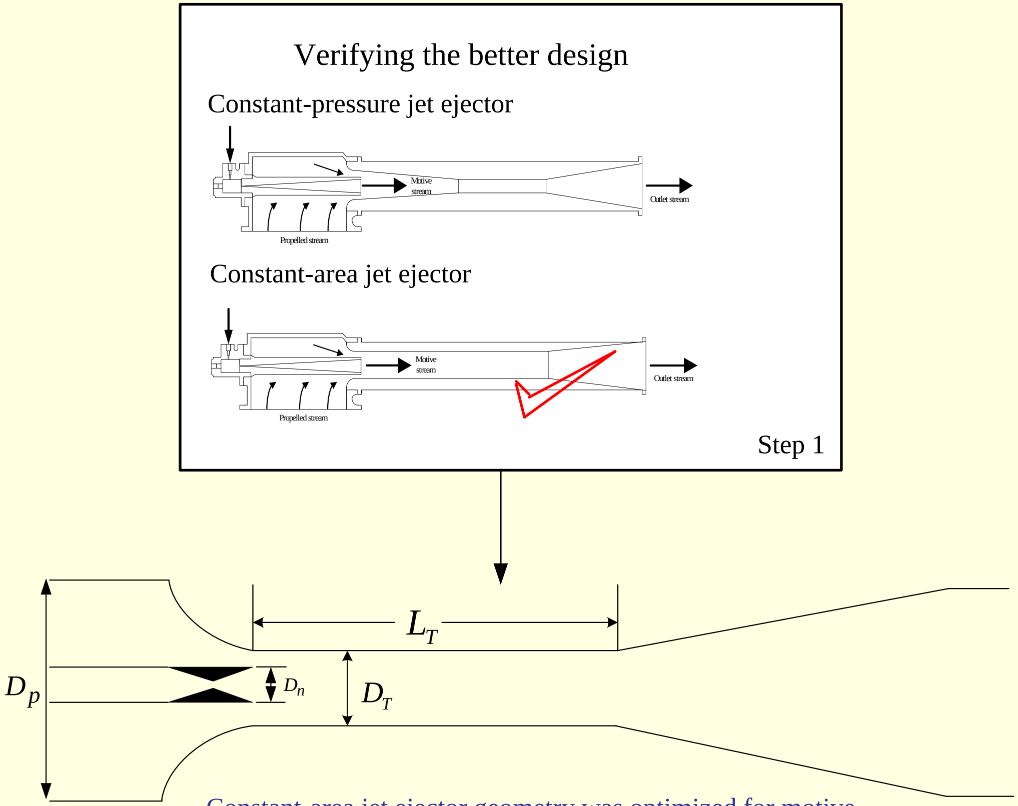
Efficiency decreases at higher mass flow ratio and motive velocity.

The efficiency decreases considerable at the mass flow ratio less than 10. But the rate of efficiency decreasing reduces at the mass flow ratio greater than 10.

The minimum efficiency is 11.79% at motive velocity 1020 m/s and mass flow ratio 100.

4.3 Alternative nozzle designs

Optimization progress



Verifying the better design

Constant-pressure jet ejector

Constant-area jet ejector

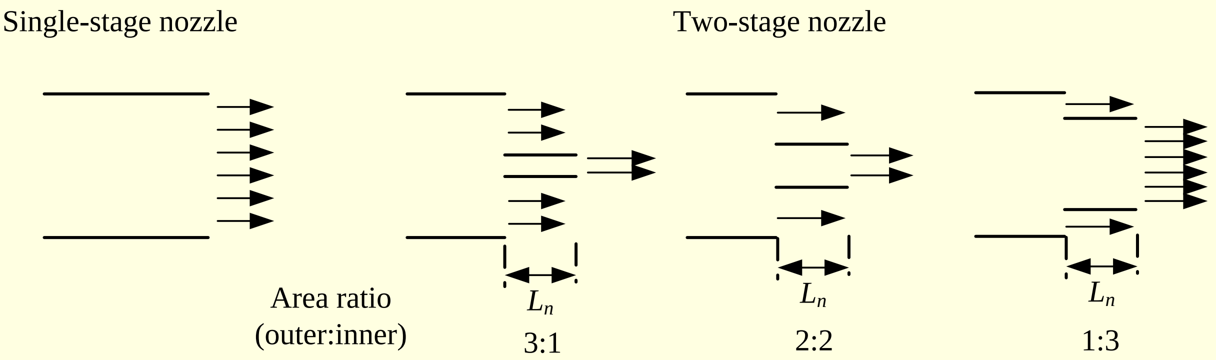
Step 1

Constant-area jet ejector geometry was optimized for motive velocity 170-1104 m/s and mass flow ratio 0.01-100.

Step 2

4.3 Alternative nozzle designs

Single-stage nozzle vs. Two-stage nozzle



Operating condition:

motive velocity 340 (low), 680 (medium), and 1020 (high) m/s and operating pressure at 1 atm.

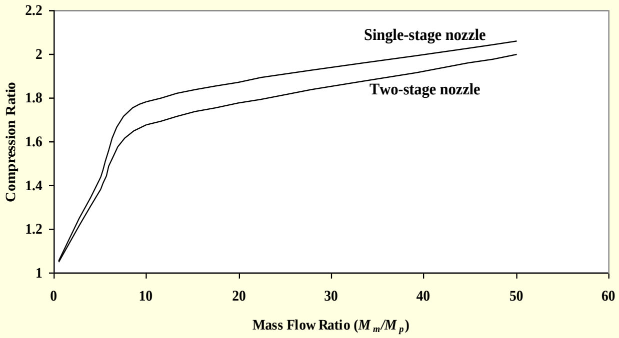
The length between two nozzle exit of each two-stage nozzle designs were optimized. The design providing the greatest jet ejector performance was selected to compare with the optimum single-stage nozzle jet ejector.

Ln = length between two nozzle exit in two-stage nozzle design

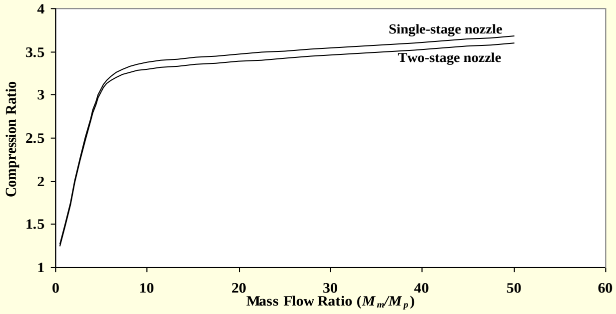
4.3 Alternative nozzle designs

Compression ratio

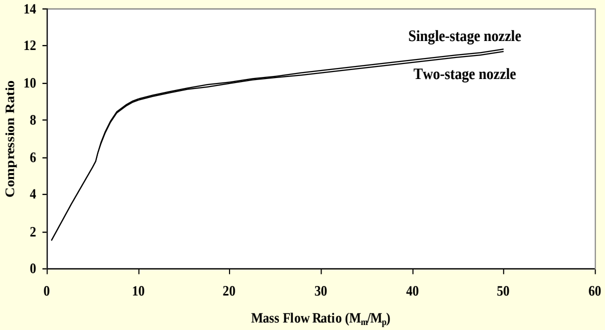
V_m = 340 m/s



V_m = 680 m/s



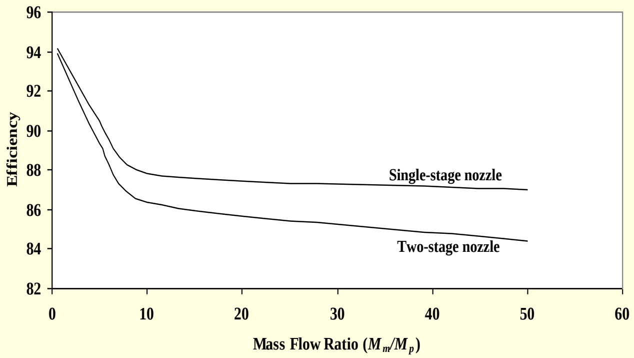
V_m = 1020 m/s

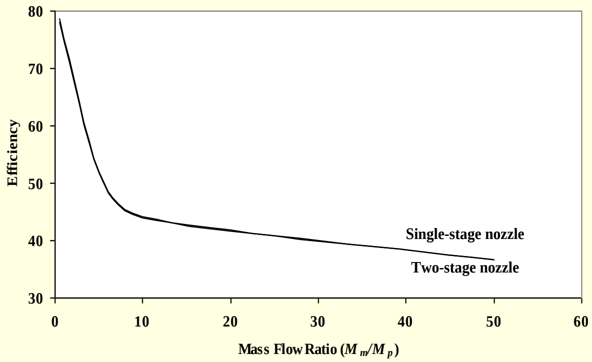


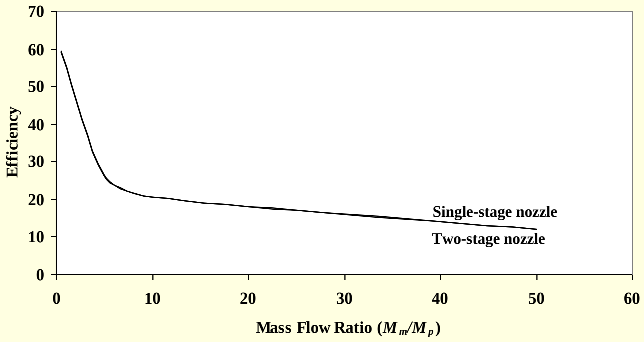
The single-stage nozzle jet ejector produces higher compression ratio for every mass flow ratio and motive velocity.

4.3 Alternative nozzle designs

Efficiency


V_m = 340 m/s

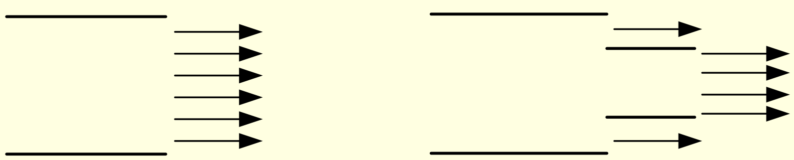

V_m = 680 m/s


V_m = 1020 m/s

The single-stage nozzle jet ejector provide higher efficiency for every mass flow ratio and motive velocity.

4.3 Alternative nozzle designs

The single-stage nozzle jet ejector provide higher on both of compression ratio and efficiency. Because the friction loss occurs at the surface between two nozzle exit in two-stage nozzle design. It reduces the jet ejector performance.



Single-stage nozzle

Two-stage nozzle

4.4 Optimization jet ejector

Optimum vs. AMETEK jet ejectors

AMETEK, Inc. is a well-known manufacture for jet ejector.

The objective is to indicate the reduction of motive-steam consumption between an optimum jet ejector and a conventional jet ejector operating in chemical industrial processes.

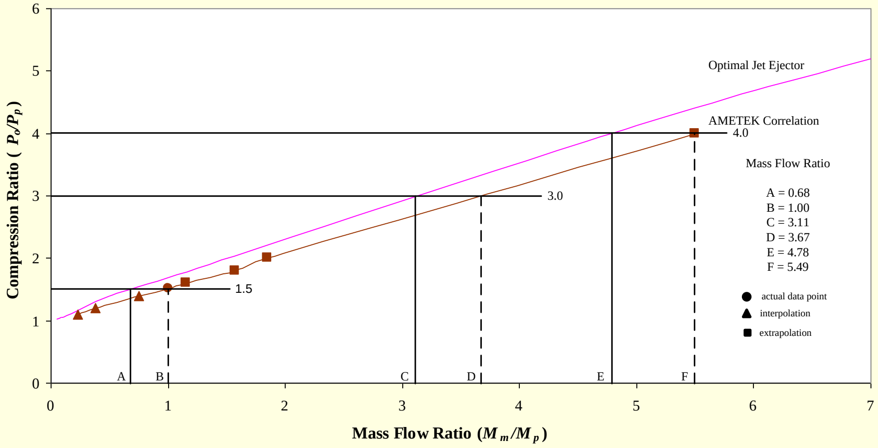
Motive velocities at 850 and 1020 m/s were selected in this analysis.

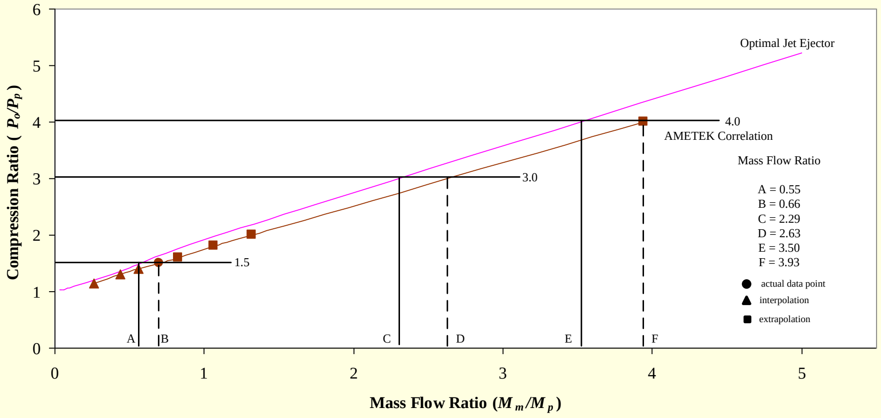
Steam is applied as a working fluid.

Total pressure at the jet ejector outlet is defined at 1 atm.

4.4 Optimization jet ejector

V_m = 850 m/s





V_m = 1020 m/s

4.4 Optimization jet ejector

Percent reduction in motive-steam usage

$$\text{Percent reduction} = \left(\frac{\text{AMETEK} - \text{Optimal}}{\text{AMETEK}} \right) \times 100$$

Compression ratio (P_o/P_p)	Percent reduction	
	Motive velocity 850 m/s	Motive velocity 1020 m/s
1.5	32.00	16.67
3.0	15.26	12.93
4.0	12.93	10.94

It appears that the optimal jet ejector consumes less motive steam than AMETEK jet ejectors by 10–30%. These simulation results must be verified by hardware.

5. Conclusions

1. In the CFD software, the average overall deviation between the simulation and experiment results is 8.19% thus confirm the accuracy of results.
2. Constant-area jet ejector produces greater performance (compression ratio and efficiency) than constant-pressure jet ejector.
3. In constant-area jet ejector, the optimum throat diameter ratio, throat length ratio, and nozzle diameter ratio are identified as the function of motive velocity (170-1104 m/s) and mass flow ratio (0.01-100).
4. Single-stage nozzle jet ejector produces a greater performance than two-stage nozzle jet ejector. Because the friction loss at surface between two nozzle exit in two-stage nozzle jet ejector causes the reduction on jet ejector performance.
5. An optimum jet ejector consumes motive-steam less than AMETEK jet ejector by 10-30%. However, the results need to be verified by hardware.

6. Acknowledgement

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