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Performance Improvement of Forced Draught Jet Ejector Using Constant Rate Momentum Change Method

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Abstract* — A jet ejector uses a jet of primary fluid to induce a peripheral secondary flow often against back pressure. Expansion of primary jet produces a partial vacuum near the secondary flow inlet creating a rapid re-pressurization of the mixed fluids followed by a diffuser to increase the pressure at the exit. Using the geometrical design parameters obtained by solving the governing equations, a CFD analysis is made using the FLUENT software to evaluate the optimum entrainment ratio that could be achieved for a given set of operating conditions, where the entrainment ratio (ER) is the ratio of the mass flow rate of the secondary fluid (propelled stream) to the primary fluid (motive fluid). The three main internal process forming sources of ejector irreversibility are mixing, kinetic energy losses, and normal shock.The CRMC method produces a diffuser geometry that removes thermodynamic shock process with in the diffuser at the design point-operating conditions. In order to match the ER that is achievable theoretically, an effort is made to force charge the propelled stream using a blower so that the momentum difference between the motive and the propelled fluid is minimized. The decrease in momentum difference increases the ER and the pressure lift ratio (P_{DE}/P_S) compared to the values obtained using the conventional methods, where P_{DE} is the exit pressure and P_S is the secondary fluid pressure. It also reduces losses due to pure mixing and kinetic energy loss.Experimental results obtained using the forced draft system is found to match the results obtained from the FLUENT analysis.

Keywords: Ejector, Efficiency, Irreversibility, CRMC, Forced draught.

I. INTRODUCTION

Ejectors are co-current flow systems, where simultaneous aspiration and dispersion of the entrained fluid takes place. This causes continuous formation of fresh interface and generation of large interfacial area because of the entrained fluid between the phases. The ejector essentially consists of an assemble comprising of nozzle, converging section, mixing throat and diffuser. According to the Bernoulli's principle when the motive fluid is pumped through the nozzle of a jet ejector at a high velocity, a low pressure region is created at just outside the nozzle. A second fluid gets entrained into the ejector through this low pressure region. The dispersion of the entrained fluid in the throat of the ejector with the motive fluid jet emerging from the nozzle leads to intimate mixing of the two phases. A diffuser section of the mixing throat helps in pressure recovery. The motive fluid jet performs two functions one, it develops the suction for the entrainment of the secondary fluid and the second; it provides energy for the dispersion of the one phase into the other. This process has been largely exploits in vacuum systems in which high speed fluid stream is used to generate vacuum. (Cramers et al) [1]

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II. CONVENTIONAL JET EJECTOR

Jet ejectors are popular in the chemical process industries because of their simplicity and high reliability. In most cases, they provide the greatest option to generate a vacuum in processes. Their capacity ranges from very small to enormous. Due to their simplicity, conventional jet ejectors that are properly designed for a given situation are very forgiving of errors in estimated quantities and of operational upsets. Additionally, they are easily changed to give the exact results required. (Mains and Richenberg) [2]

Jet ejectors provide numerous advantages, which are summarized below:

1. It does not require extensive maintenance, because there are no moving parts to wear.
2. It has lower capital cost comparing to the other devices, due to their simple design.
3. They are easily installed, so they may be placed in inaccessible places.

On the other hand, the major disadvantages of jet ejector follow.

1. They are designed to perform at a particular optimum point. Deviation from this optimum point can dramatically reduce ejector efficiency.
2. It has very low thermal efficiency.

2.1 Jet Ejector Application

Due to their simplicity, jet ejectors have been used for various purposes. A number of the principle applications are listed below. (Schmitt) [3]

1. Extraction: suction of the induced fluid.
2. Compression: compression of the induced fluid using a motive fluid.
3. Ventilation and Air-conditioning: extraction and discharge of gas near atmospheric pressure with small compression ratio.
4. Thermo-compression desalination: pressurizing water vapors from evaporating saline water (Porteous, 1983).
5. Supercharging: supercharging is achieved using a jet compressor by re-circulating the exhaust gas.

2.2 Operating Principle.

As shown in Figure 1, the conventional jet ejector design has four major sections:

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1. Nozzle 2. Suction chamber 3. Throat 4. Diffuser

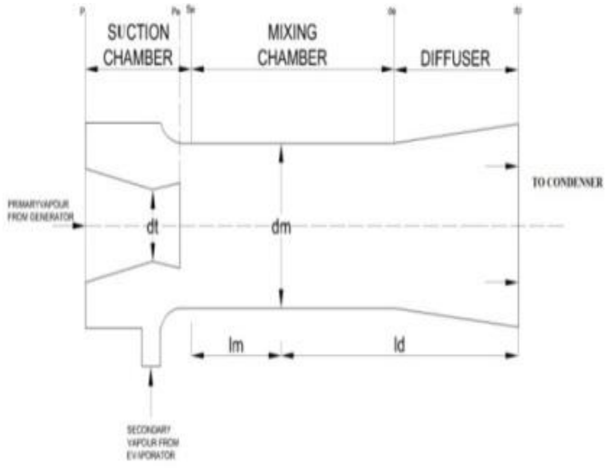

Figure1. Conventional jet ejector design

The operating principle of ejector is described below:

- A subsonic motive stream enters the nozzle. The stream flows in the converging section of the nozzle, its velocity increases and its pressure decreases. At the nozzle throat, the stream reaches sonic velocity. In the diverging section of the nozzle, the increase in cross sectional area decreases the shock wave pressure and its velocity increases to supersonic velocity
- The entrained fluid enters the ejector. Its velocity increases and its pressure decreases. The motive stream and entrained stream mix within the suction chamber and the converging section of the diffuser, or they flow as two separate streams and mix together in the throat.
- In either case, there is a shock wave inside the throat section. The shock results from the reduced mixture velocity to a subsonic condition and the back pressure resistance of the condenser.
- The mixture flows into the diverging section of the diffuser. The kinetic energy of the mixture is transformed into pressure energy. (EI-Dessouky et. al) [4]

When the working fluid passes through ejector, it is subjected to losses of flow due to fluid and wall frictions at different sections. These losses are accounted in terms of efficiencies referred to ideal isentropic transforms. They are generally identified on the basis of the flow passage like nozzle efficiency for primary fluid flow, suction or secondary fluid flow efficiency, mixed fluid flow efficiency and diffuser efficiency. (Selvaraju) [5].

III. VARIOUS LOSSES IN JET EJECTOR

There are three main losses occurs in the Jet ejector

1. Pure Mixing loses, 2. Kinetic energy loses, 3. Shock wave loses In order to define sources of losses in ejector performance, an equivalent ideal process should be theoretically defined as a process with no entropy production. When applicable, such "ideal" process is equivalent to a reversible process from a thermodynamic point of view. In a mixing process, which cannot be reversible, the "ideal process" represents on with an upper limit of performance.(A. Shklyar et al) [7]. The ejector includes three main sources of irreversibility "pure mixing" "kinetic energy losses," and normal shock wave. The "pure mixing" and "kinetic energy losses" occur simultaneously in the mixing section followed by the normal shock wave (which is in constant-area section).[7]

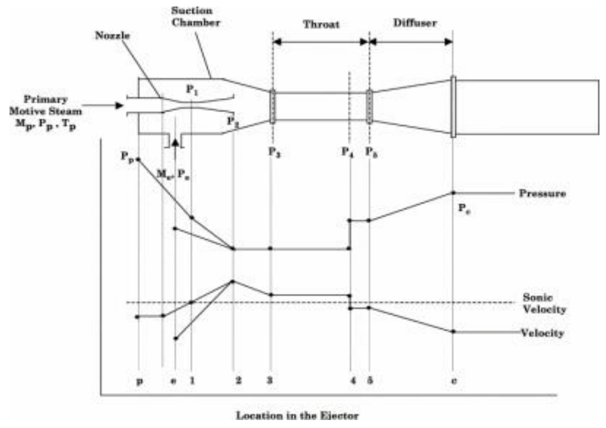

Figure 2.Illustrates the shock wave occurring inside the jet ejector

IV. A DESCRIPTION OF THE CONSTANT RATE OF MOMENTUM CHANGE METHOD

The CRMC method, (I.W. Eames) [9] produces a diffuser geometry that removes the thermodynamic shock process within the diffuser at the design-point operating conditions. This achieved by allowing the momentum of the flow to change at a constant rate as it passes through the diffuser passage, which allows the static pressure to rise gradually from entry to exit, avoiding the total pressure loss associated with in shock process encountered in conventional diffusers. Eq. (1) describes the CRMC assumption:

Where β = constant.

$$\frac{d\dot{M}o}{dx} = \dot{m}_g (1+R_m)\frac{dc}{dx} = \beta \quad (1)$$

For the purpose of explanation and in order to specify the geometry of the flow passage through the diffuser the following further assumptions are made:

1. The same gas is assumed for both primary and secondary flows.
2. The process gas is assumed to be ideal.
3. The total pressures and temperatures of the primary and secondary flows are known.
4. The flow is assumed to be adiabatic throughout.
5. The velocity of the secondary flow at entry to the entrainment region (C_s) is specified.
6. The entrainment process is carried out at constant static pressure equal to $P_s = P_{NE}$.
7. At the design condition the combined primary and secondary flow stream is compressed within the diffuser section so that at its throat the local Mach number equals unity.
8. The primary mass flow ($\dot{m}g$), and the required entrainment ratio (R_m), are specified.

Referring to Fig. 3 the boundary conditions for Eq. (1) are

CDx = C_1 at x = 0 and CDx = CDE at x = L_D

Where C_{DE} is the selected combined flow velocity at diffuser exit plane in Fig. 3. Solving Eq. (1) using the above boundary conditions yields

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$$CDx = C_1 - \frac{(C_1 - C_{DE})x}{L_D} \quad \text{for } 0 \le x \le L_D \quad (2)$$

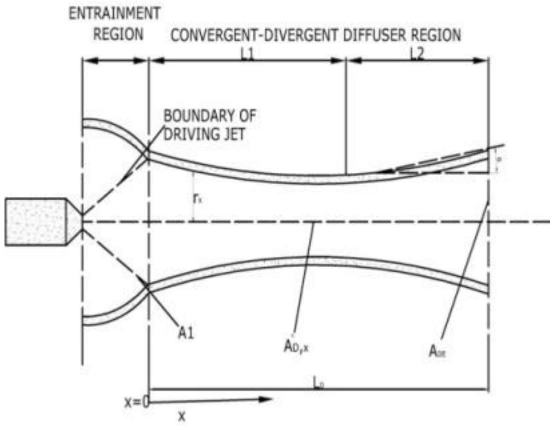

Figure.3 Schematic view of a turbine compressor

V. HIGH EFFICIENCY JET EJECTOR

The primary concept to improve jet ejector performance is to minimize momentum differences between the motive and propelled streams. (SomsakWatanawanavet) [10].A mathematical calculation compares small and large momentum differences between the motive and propelled streams.

M_m = 1.0 kg/s ν_m = 10 m/s$M_{mixture}$ = 2.0 kg/s

M_p = 1.0 kg/s ν_p = 1 m/s $\nu_{mixture}$ = 5.5 m/s

Figure.4 Diagram of large momentum different condition.

The total kinetic energy before mixing is the sum of the kinetic energy between the motive and propelled stream. The kinetic energy of motive stream is:

$$E_{km} = \frac{1}{2} M_m \nu_m^2 = \frac{1}{2}.\ (1\,\text{kg/s}).\ (10\,\text{m/s})^2 = 50\ \text{J/s} \quad (3)$$

Where,

E_{km} = kinetic energy of the motive stream (J)

M_m = mass flow mate of the motive stream (kg/s)

ν_m = velocity of the motive stream (m/s)

The kinetic energy of the propelled stream is:

$$\left[E_{kp} = \frac{1}{2} M_p \nu_p^2 = \frac{1}{2}.\ (1\ \text{kg/s}).\ (1\,\text{m/s})^2 = 0.5\ \text{J/s} \quad (4)\right]$$

Where,

E_{kp} = kinetic energy of the propelled stream (J)

M_p = mass flow rate of the propelled stream (kg/s)

ν_p = velocity of the propelled stream (m/s)

From mass conservation, the mass flow rate of the mixture stream is the sum of the motive and propelled streams.

$M_{mixture}=M_m+M_p=1+1=2$kg/s (5)

Where, $M_{mixture}$ = mass flow rate of the mixture stream (kg/s)

The velocity of the mixture stream is computed by momentum conservation, as shown in the next step.

$P_{mixture} = P_{motive} + P_{propelled}$ (6)

Where,

$P_{mixture}$ = momentum of the mixture stream (kg. m)/s

P_{motive} = momentum of the motive stream ((kg . m)/s

$P_{propelled}$ = momentum of the propelled stream ((kg. m)/s

So,

$M_{mixture}\nu_{mixture} = M_{motive}\nu_{motive} + M_{propelled}\nu_{propelled}$ (7)

Where,

$M_{mixture}$ = mass flow rate of the mixture stream (kg/s)

$V_{mixture}$ = velocity of the mixture stream (m/s)

Thus

$$\nu_{mixture} = \frac{M_{motive}\ \nu_{motive} + M_{propelled}\ \nu_{propelled}}{M_{mixture}} = \frac{(1\ \text{kg/s}\ .\ 10\ \text{m/s}) + (1\ \text{kg/s}\ .1\ \text{m/s})}{2\ \text{kg/s}} = 5.5\ \text{m/s}$$

The kinetic energy of the mixture stream is

$$E_{kmix} = \frac{1}{2} M_{mix}\ \nu_{mix}^2 = \frac{1}{2}.\ (2\ \text{kg/s}).\ (5.5\ \text{m/s})^2 = 27.5\ \text{J/s} \quad (9)$$

Where,

E_{kmix} = kinetic energy of the mixture stream (J)

Energy efficiency is calculated by:

$$\eta = \frac{E_{kmix}}{E_{km} + E_{kp}} = \frac{27.5\ \text{J}}{50\ \text{J} + 0.5\ \text{J}}\ 0.545 \quad (10)$$

Where,

η = efficiency

In the small momentum different case, the velocity of the propelled stream is increased from 1 to 6 m/s (see Figure 5).

M_m = 1.0 kg/s ν_m = 10 m/s M_p = 1.0 kg/s

$M_{mixture}$ = 2.0 kg/sν_p = 6 m/s$\nu_{mixture}$ = 8 m/s

Figure 5. Diagram of small momentum different condition.

Following the above calculation, the kinetic energy of the motive stream is

$$E_{kmix} = \frac{1}{2} M_{mix}\ \nu_{mix}^2 = \frac{1}{2}.\ (2\ \text{kg/s}).\ (8\ \text{m/s})^2 = 64\ \text{J/s} \quad (11)$$

The kinetic energy of the propelled stream is:

$$E_{kp} = \frac{1}{2} M_p\ \nu_p^2 = \frac{1}{2}.\ (1\ \text{kg/s}).\ (1\ \text{m/s})^2 = 18\ \text{J/s} \quad (12)$$

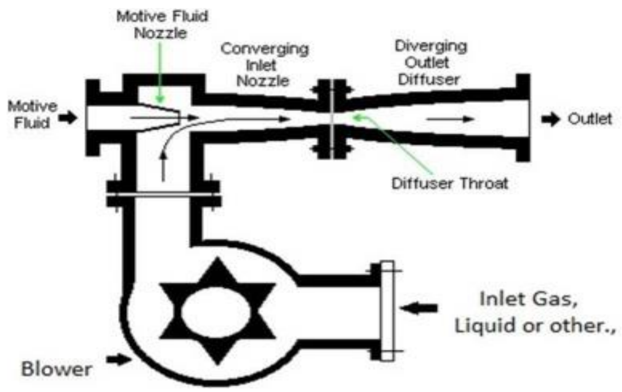

Figure.6. High Efficiency Jet Ejector with blower (Forced Draught)

The kinetic energy of the mixture stream is:

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$$E_{kmix} = \frac{1}{2} M_{mix} v_{mix}^2 = \frac{1}{2} . (2 \text{ kg/s}). (8 \text{ m/s})^2 = 64 \text{ J/s} \quad (13)$$

The resulting efficiency is:

$$\eta = \frac{E_{kmix}}{E_{km} + E_{kp}} = \frac{64 \text{ J}}{50 \text{ J} + 18 \text{ J}} = 0.941 \quad (14)$$

The calculation shows the efficiency increases substantially when the momentum difference between the motive and propelled streams decreases. This is achieved by increasing the velocity of the propelled fluid using a blower keeping the mass flow as constant.

VI.RESULTS AND DISCUSSION

Figure (7) shows the velocity contour map inside the jet compressor without forcing the secondary fluid. It is seen from the contour plot that the maximum flow velocity occurs at the exit of the primary nozzle of the compressor, after which the velocity decreases because of exchange of momentum and mixing with the secondary fluid stream. It is also observed that due to the boundary layer effect a velocity gradient is observed from the wall to the center line flow of the jet compressor. The sectional view AA shows the conversion of pressure energy to kinetic energy as the flow becomes supersonic. At the throat, due to momentum exchange with the secondary fluid the flow becomes almost sonic. Further, in the diffuser section the remaining kinetic energy is converted to pressure energy.

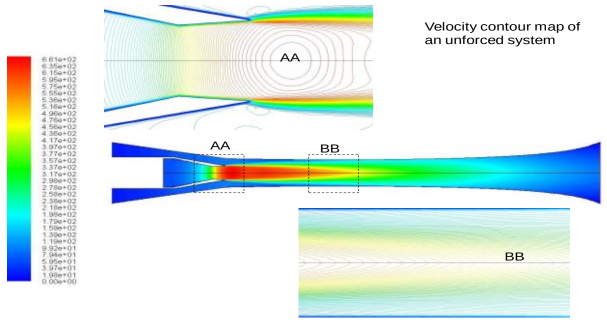

Figure 7. The Velocity vector map showing the maximum velocity occurring at the primary jet nozzle of the jet compressor for an unforced entrainment. The sectional view AA shows the flow velocity of the motive fluid and view BB shows the flow velocity after mixing of motive and propelled fluids.

Figure (8) shows the velocity contour map inside the jet compressor when a blower is used to force the secondary fluid. At the exit of the primary nozzle, it is observed that the flow has the maximum velocity similar to the maximum flow velocity observed in the unforced system. Since the secondary fluid is forced with higher inlet velocity using the blower, lesser amount of momentum is exchanged with the motive fluid. Due to the minimum momentum difference, the loss of kinetic energy of the motive fluid during mixing is also minimized.

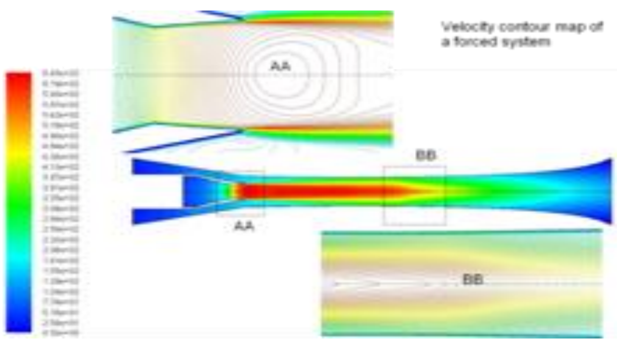

Figure.8. The Velocity contour map showing the maximum velocity occurring at the primary jet nozzle of the jet compressor for a forced entrainment. The sectional view AA shows the flow velocity of the motive fluid and view BB shows the flow velocity after mixing of motive and propelled fluids.

This resulted in increased entrainment of secondary fluid and higher ER. Sectional view BB clearly shows the flow field of the mixed fluid having much higher velocity than that of the unforced flow at the entry of the diffuser section. The sectional view AA shows the conversion of flow from subsonic to supersonic as seen in the unforced system.

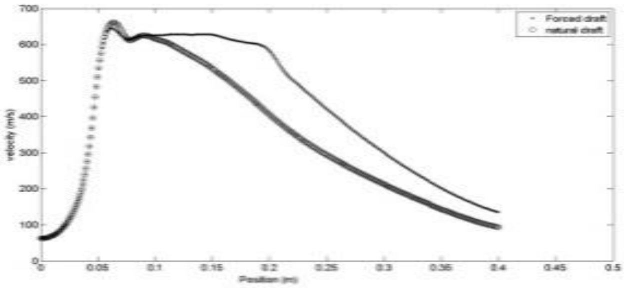

Figure.9. Variations of flow velocity at different sections of the jet compressor

The flow velocity plot obtained from the simulation results both for forced and unforced draft jet compressor are shown in figure (9). The steep rise in velocity for the initial length 50mm of the jet compressor corresponds to the flow expanding at the primary nozzle where the pressure energy is converted into kinetic energy. At the end of the primary nozzle, the flow changes from subsonic to supersonic condition which is responsible for the entrainment of the secondary fluid. Since, the secondary fluid is forced externally using a blower, it is observed that the velocity of the motive fluid is almost maintained constant till the end of compressor throat compared to the natural draft system after an initial drop in velocity at the mixing section. This ensures a minimum momentum difference between the motive and the propelled fluid by which the entrainment ratio of the jet compressor is increased. In the diffuser section of the jet compressor the flow velocity of the mixed fluid decreases again to subsonic velocity converting the kinetic energy to pressure energy.

The static pressure variation at various sections in the jet compressor for an unforced system is shown in Figure (10). Exhaust gas from the internal combustion engine enters the jet compressor as motive stream at an absolute pressure of 3.5 bars. It expands in the nozzle and comes out at a reduced pressure of 0.5 bar. Due to the low pressure developed at the nozzle exit, atmospheric air is sucked through the convergent region of secondary nozzle. Both the streams get mixed in the mixing chamber at approximately constant pressure and enter into the diffuser. In the diffuser section the pressure of the mixed stream increases to the outlet pressure of 1.5 bars (absolute).

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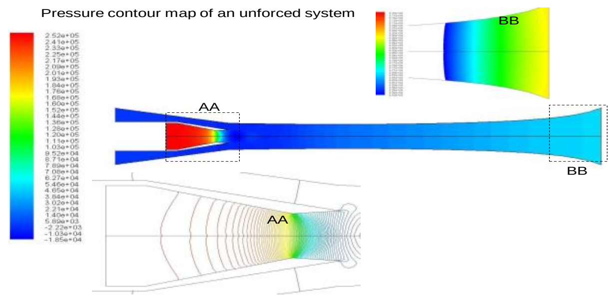

Figure.10. The static pressure variation in the jet compressor for an unforced system. The sectional view AA shows the conversion of pressure energy of the motive fluid to kinetic energy at the primary nozzle and view BB shows the variation of exit pressure of the jet compressor after mixing.

Figure (11) shows the variation of static pressure (gauge) variation along the axis of the jet compressor for a forced system. It is observed from the contour that the maximum pressure drop of the motive stream occurs at the primary nozzle exit where it is reduced below the atmospheric pressure. This low pressure causes the secondary fluid to be sucked into the mixing chamber where it is mixed with the secondary streams increasing the pressure of the mixture to nearly atmospheric pressure.

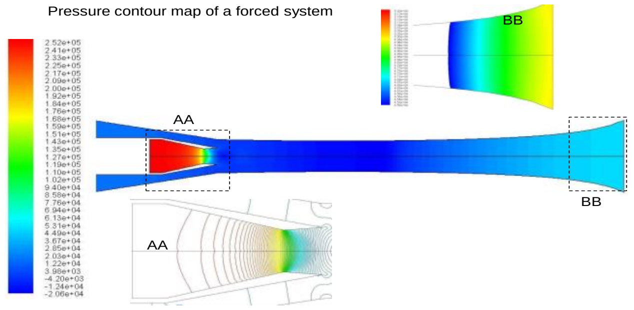

Figure. 11. The pressure contour map of the jet compressor for a forced entrainment. The sectional view AA shows how the pressure energy of the motive fluid is converted into kinetic energy at the primary nozzle and view BB shows the variation of exit pressure of the jet compressor after mixing.

As explained above, the shock waves are avoided by modifying the geometric parameters of the converging and diverging sections of the jet compressor as per the geometrical parameters calculated using the CRMC method. Hence, the pressure rise in the diffuser section is gradual till it reaches the outlet pressure.

VII. CONCLUSION

By comparing the simulation results obtained from both the forced, using blower and the unforced suction of a jet compressor, it was evident that the minimization of the momentum difference between the motive and the propelled fluids enhanced the ER to 1.5 closely matching the theoretical estimates of 1.8 for a given operating condition. Further by forcing the secondary fluid using a blower resulted in the overall increase of the jet compressor efficiency. Using CRMC method the estimated pressure lift ratio was found to increase by 40% over conventional method.

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