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Optimization of Supersonic Ejector by Condensing Rocket Plume

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Abstract
Ejectors are used in the High Altitude Test (HAT) facility to maintain a vacuum inside the test chamber and reducing exhaust backflow into the test chamber. The performance of the ejectors depends on mass flow rate of primary fluid and the secondary fluid. If the exhaust mass from the rocket engine is higher, then it requires high amount of driving fluid(gaseous nitrogen /steam / air) to maintain a vacuum inside the test chamber.If the exhaust mass from the rocket engine is reduced, then the requirement of driving fluid also be reduced. Cryogenic engine plume contains 98% of water molecules, which can be condensed to reduce the ejector load. In this investigation, exhaust mass from the engine is reduced by using the heat exchanger. Exhaust mass temperature also be reduced from 450K to 380 K to optimize the ejector performance. CFD analysis is used to determine the ejector performance at various inlet conditions.

1. Introduction

The key purpose of high altitude testing is to obtain a better simulation or visualization of the rocket's operating environment [1]. It is a well known fact that the air pressure decreases as increasing the altitude. Design of an altitude experimental facility is much more complex than a sea level facility. Lower air pressure effects include higher rocket thrust and lower heat transfer. The cryogenic rocket engine is installed inside an enclosed chamber which is evacuated to a minimum pressure level before rocket firing. A typical chamber operating pressure (equivalent to an altitude of 100,000 feet) is achieved inside the chamber by some form of mechanical pumping. Typically, mechanical pumping is achieved by steam ejector/diffusers. If the combustion products from the rocket firing include flammable or explosive materials, the chamber should be inerted, typically with gaseous nitrogen [1]. The inerting process prevents the build-up of explosive materials inside the chamber or exhaust ducting. During steady state operation of a typical cryogenic engine, plume mass flow rate from the engine is about 46.2 kg/s. If only vacuum pumps are used for sucking the exhaust flow from the engine, then the overall capacity of the pump should be very high. It is impossible and the second feasible way is to use a simple diffuser. But the simple diffuser system is applicable only if the exhaust momentum is sufficient to push the shock developed in the nozzle beyond the second throat of the diffuser during starting. Otherwise, the shock will be positioned in the convergent portion of the diffuser and it leads to unstable condition. As a result, the shock travels back towards the engine and eventually enters into the engine nozzle. It causes the flow separation with a thick turbulent boundary layer in the divergent portion of the nozzle. The major HAT system components and the associated setup are illustrated in Fig 1.

The third possibility is to use an ejector system. If ejector system alone is used for pumping the exhaust gas from the engine, it requires huge amount of driving fluid. If the ejector system is combined with the diffuser system, then the workload can be shared by both the systems. Furthermore, the loads acting on ejectors can also be reduced and because of this motivation, often a blended ejector-diffuser system is preferred [2].

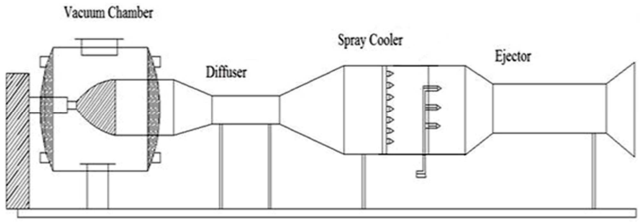

Figure 1. *Present HAT system.*

If the exhaust mass from the rocket engine is higher, then it requires high amount of driving fluid (gaseous nitrogen) [1] to maintain a vacuum inside the test chamber. If the exhaust mass from the engine is reduced, then the requirement of GN_2 is also reduced. For this required function, heat exchanger is proposed to be introduced in the upstream part of ejector. The propulsive efficiency of a clustered nozzle configuration increases by condensing the exhaust plumes in the early versions of rocket engines. However, the condensation process was accomplished by a separate unit consists of complex instrumentation and control systems.

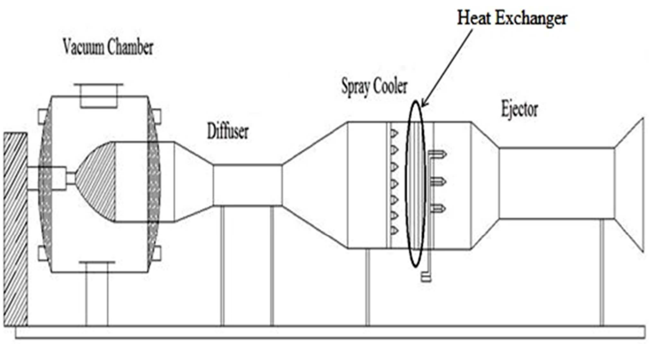

Figure 2. *Modified HAT system facilit.*

In the modified HAT setup displayed in Fig 2, heat exchanger is introduced between the isolation valve and ejector system. This heat exchanger condenses the exhaust plume from the rocket engine. Thereby quantity of exhaust plume from the engine will be reduced and the ejector performance is enhanced [3]. It is a novel approach to condense the exhaust plumes with relatively simple thermodynamic concepts.

2. Heat Exchanger Selection

Shell and tube heat exchanger is preferred for the exhaust plume condensation process [4]. This type of heat exchanger consists of a shell with a bundle of tubes. Cold water runs through the tubes, and hot steam flows over the tubes (through the shell) to transfer heat between the two fluids [5]. Overall length of the heat exchanger is about 6 m and the diameter is 3 m. Heat is transferred from one fluid to the other through the tube walls, from tube side to shell side or shell side to tube side. Shell and tube heat exchangers provide large ratios of heat transfer area to volume [5]. The cleaning process for type of heat exchanger is easy and simple one [6]. Because of all these merits, shell and tube heat exchanger is preferred in the present investigation.

3. Design of Heat Exchanger

The log mean temperature difference ΔTlm (LMTD) for counter current flow [7] is given by:

$$\Delta Tlm = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \dfrac{(T_1 - t_2)}{(T_2 - t_1)}} \tag{1}$$

Where,
T_1- Hot fluid inlet temperature
T_2- Hot fluid outlet temperature
t_1- Cold fluid inlet temperature
t_2- Cold fluid outlet temperature
Overall heat transfer co-efficient [7] is given by,

$$U = \frac{1}{\dfrac{1}{h_i} + \dfrac{1}{h_o} + \dfrac{L}{K}} \tag{2}$$

Where,
h_i- Inner side heat transfer coefficient
h_o- Outer side heat transfer coefficient
L - Shell thickness
K -Thermal conductivity
Total area required,

$$\mathrm{A} = \frac{Q}{F \times \Delta Tlm} \tag{3}$$

Where,
F- Fouling factor
Q- Heat transfer rate

Reynolds number [8], $\mathrm{Re} = \dfrac{\rho v d}{\mu}$

Nussalt number [8], $\mathrm{Nu} = 0.027\,\mathrm{Re}^{0.8} \times \mathrm{Pr}^{0.333} \times \left(\dfrac{\mu_m}{\mu_w}\right)^{0.14}$

The required numbers of tubes [9] are calculated from the equation,

$$\mathrm{N_T} = \frac{A}{\pi \times d \times L} \tag{4}$$

Baffle spacing, $Bs = 0.4 \times Ds$

Where,

A- Total area

d- Diameter of tube

L- Length of the tube

Required heat transfer area for reducing the temperature from 450 K to 380 K, required number of tubes, number of baffles, baffle spacing and tube pitch are calculated from equations (1) – (4).The shell and tube heat exchanger components such as tubes, tube sheets, baffles, shell and shell head are designed using the modelling software (CATIA V5). The various components of heat exchanger are modelled as displayed in Figure 3. The assembled view of the components 3 (a) to 3 (e) is presented in Fig 3 (f).

Table 1. *Shell and tube heat exchanger design specifications.*

1	**Shell inner dia**	**3m**
2	Number of tubes	233
3	Tube outer dia	0.1m
4	Tube inner dia	0.095m
5	Tube thickness	0.005m
6	Shell thickness	0.01m
7	Tube pitch	0.168m
8	Number of baffles	4
9	Baffle spacing	1.2m
10	Height of baffle	2.25m

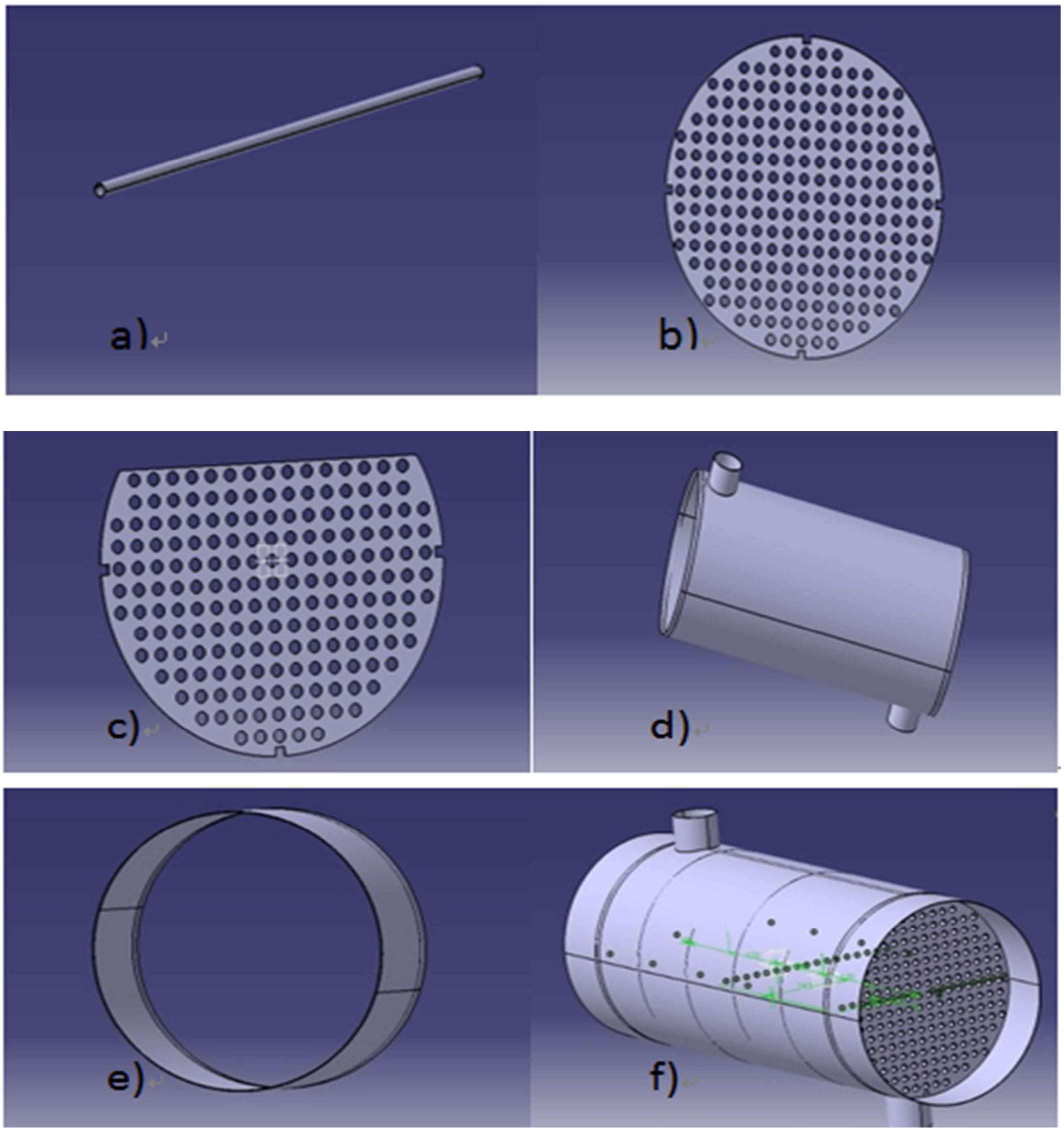

Figure 3. *Heat exchanger components modeling.*

a) Tube
b) Tube sheet
c) Baffle
d) Shell
e) hell head
f) Heat exchanger assembly

4. Selection of Tube Material

The tube material should contain better thermal conductivity to ensure the superior heat transfer properties [6]. Because heat is transferred from hot fluid to cold fluid through the tube walls and there should be a temperature difference through the width of the tubes. Because of the predilection of the tube material to thermally expand differently at various temperatures, thermal stress occurs throughout the operation. It is the stress in addition to any other working stress caused by high pressures from the fluids themselves. One of the selection criteria for heat exchanger material depends on the corrosiveness of the working fluid. Stainless steel and AISI 302 are having good thermal conductivity and corrosion resistance. Hence, Stainless steel and AISI 302 are preferred as a tube and shell materials respectively.

Table 2. *Properties of stainless steel AISI 302 at 27° C.*

Properties	Value
Density	8055 kg/m3
Thermal conductivity	15.1 W/mK
Specific heat	480 J/kgK
Thermal Diffusivity	3.91×10-6 m2/s
Modulus of elasticity	193 GPa
Poisson's Ratio	0.25
Melting Point	1400 - 1420 °C
Shear Modulus	77.2 GPa
Fatigue Strength	485 - 550 MPa

5. Ejector Design

Main Ejector system consists of high pressure cylinders, flow components, convergent-divergent nozzle, and an ejector shroud.

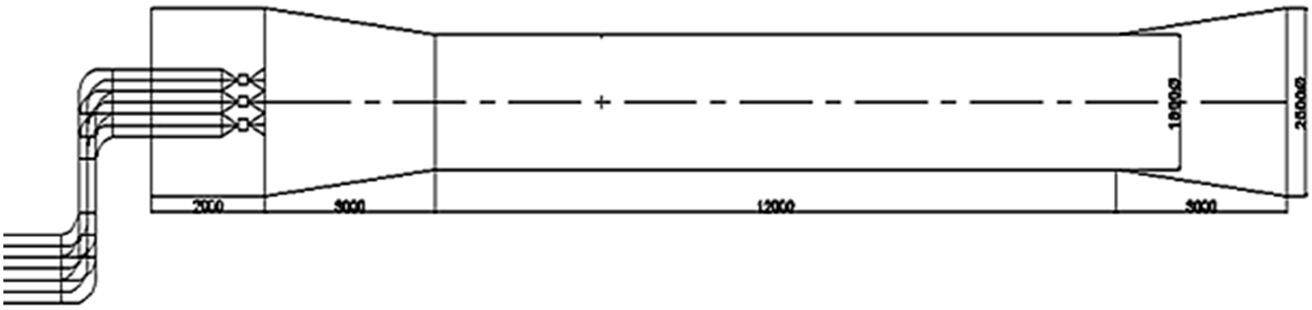

Figure 4. *Configuration of ejector system.*

The configuration of an ejector system in the high altitude test facility with GN_2 is used as a driving fluid is presented in Figure 4. Gaseous Nitrogen is preferred as a compromise between air and steam because of its functionally that is similar to air. It can be stored well in advance in the high pressure GN_2 storage tanks.

Chocked conditions at the active fluid nozzle throat [10],

$$m_a = P_{a_0}.A_{a_1} \times \sqrt{\frac{\gamma_a}{R_a T_{a_0}}} \times \sqrt{\left(\frac{2}{\gamma_a + 1}\right)^{\frac{\gamma_a+1}{2(\gamma_a-1)}}}$$

Where,

Pa_0- Active gas supply pressure

Aa_1 - Primary nozzle throat area

Ra - Gas constant for active fluid

Ta_0- Temperature of active fluid

In the present condition (before modifying the HAT facility), the secondary mass flow rate through the ejector is around 200 kg/s. By introducing the heat exchanger, the mass flow rate is reduced to 159 kg/s.

Rate of Condensation [11] is calculated from, m = $\frac{\dot{Q}}{h_{fg}}$

Heat transfer rate [11] is calculated from the following equation, $\dot{Q} = h_{av}.A(T_{sat} - T_w)$

Where,

h_{av}- Average heat transfer coefficient

A - Heat Exchanger area

T_{sat}- Saturation temperature

T_W - Wall temperature

The ejector nozzle has to be designed to deliver 300 kg/s of GN_2. Since the quantity of ejector fluid to be handled is very high, it is quite difficult to fabricate the ejector system as a single unit. Moreover large size flow components for this GN_2 line are also not available commercially. In the view of this motivation, designing a single ejector system is not advisable [12]. Hence, four ejector nozzles (cluster nozzle) configuration is preferable than a single nozzle. In this arrangement, each ejector nozzle has to handle the mass flow about 75 kg/s of GN_2 only.

5.1. Numerical Simulation

CFD analysis is conducted to study the performance of the ejector system and it will be validated using the theoretical results. Based on the theoretical results, the configuration of the systemis finalized. The clustered nozzle configuration of the HAT ejector system is modeled and meshed using Finite Element Analysis tool (ANSYS FLUENT). The second throat diffuser geometry offers high pressure energy for the engine plumes from the extracted kinetic energy of the spray cooled gas [13].

The flow and geometry similarity assumptions are maintained and quarter portion of the domain is considered for the present analysis. The performances of the ejector with and without heat exchanger are analyzed for various supply pressure input conditions.

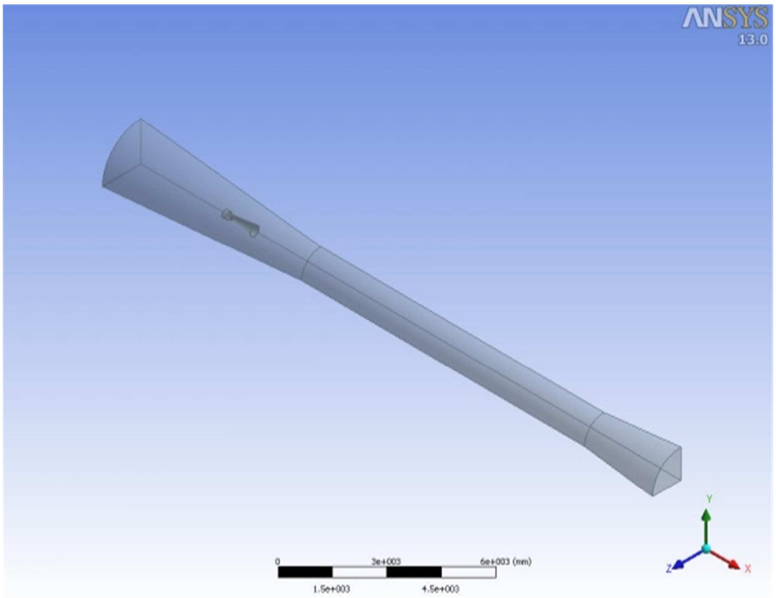

Figure 5. *Ejector model (90º sector.)*

5.2. Boundary & Initial Conditions

Pressure inlet boundary condition is defined at the ejector nozzles inlet with the Nitrogen gas pressure of 24 bar with gas temperature about 280 K. Ejector exit is defined with pressure outlet boundary. Mass flow inlet boundary is defined at the secondary inlet with 50 kg/s mass flow rate for present condition and 40 kg/s for modified conditions. No slip condition at the wall and the symmetric condition at the planes of symmetry. The entire computational domain is initialized with the atmospheric condition.

6. Results and Discussion

In the present HAT facility, if all the four ejector nozzles are working with 24 bar GN_2 supply pressure, then the ejector is competent to generate the suction pressure of 857 mbar for input conditions. Conversely, in the modified HAT facility, for the same input conditions,729 mbar suction pressure is achieved. The static pressure contour for 24 bar supply pressure without the heat exchanger configuration is highlighted in Fig 6.

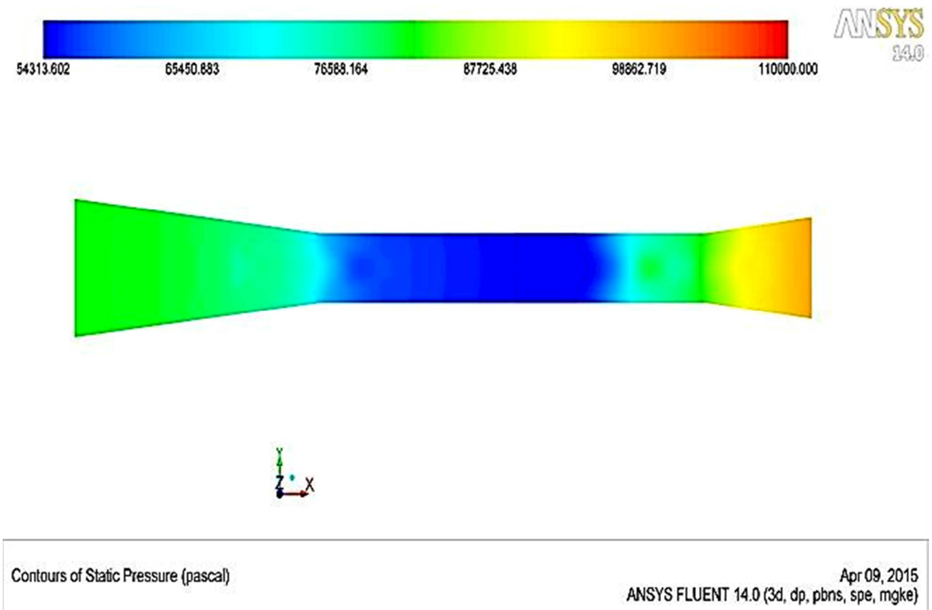

Figure 6. *Static pressure contour without heat exchanger (Pa).*

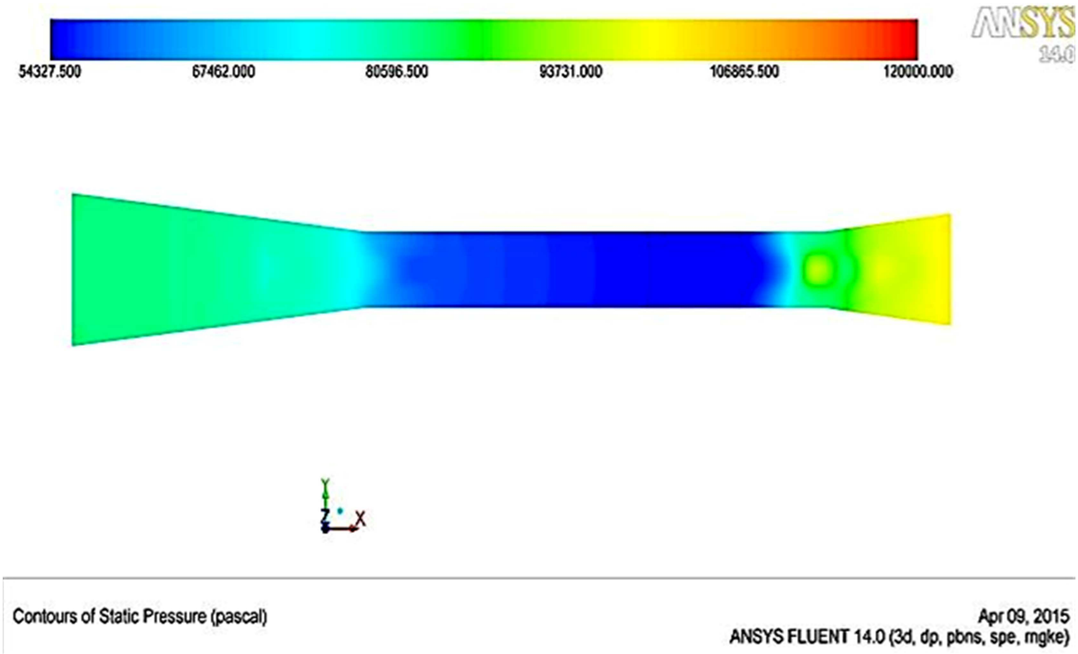

Figure 7. *Static pressure contour with heat exchanger (Pa.)*

The static pressure contour for 24 bar supply pressure with the heat exchanger configuration is highlighted in Fig 7.The static pressure enhancement is obtained at the outlet of the ejector unit because of the presence of heat exchanger. In the similar fashion, for various primary nozzle supply pressures, the computed suction pressures are listed in Table 3. The dynamic pressure and temperature distributions are also computed to investigate the effect of heat exchanger on the output parameters.

Table 3. *Obtained Suction pressure with and without heat exchanger.*

GN2 supply pressure (bar)	Suction pressure in present condition (mbar)	Suction pressure in modified condition (mbar)
26	862	736
24	857	729
22	860	777
20	869	815
18	884	855
16	905	863
14	939	885
12	996	934
10	1048	987

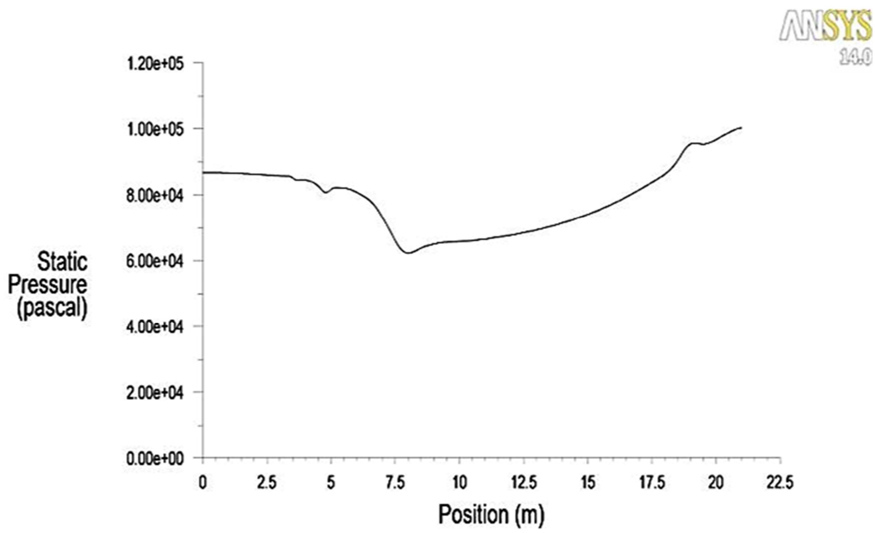

Figure 8. *Ejector suction pressure without heat exchanger at 24 bar supply pressure.*

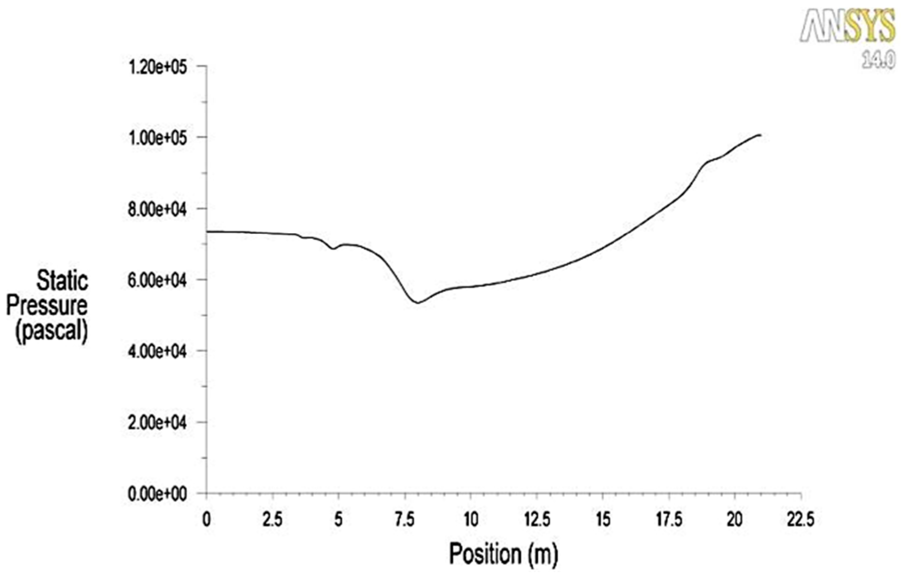

Figure 9. *Ejector suction pressure with heat exchanger at 24 bar supply pressure.*

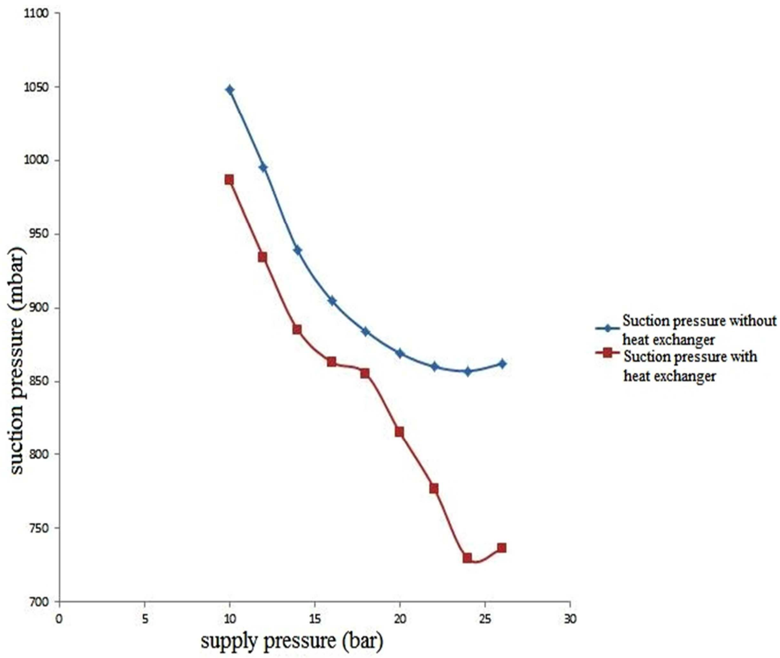

Figure 10. *Suction pressure with heat exchanger and without heat exchanger.*

The performance analysis of an ejector system in the present as well as and in the modified conditions is compared as illustrated in Fig 10. At 10 bar supply pressure, in the present system, ejector produces 1048 mbar suction pressure while in modified conditions, it produces about 987 mbar suction pressure. For Cryogenic rocket engine testing in the HAT facility, the required suction pressure for enhanced performance is about 850 mbar. However, for all kinds of liquid propellant rocket engines, an enhanced performance can be expected as the outcome of condensing the exhaust plumes rapidly.

At present, the space research organizations around the globe use 24 bar GN_2 supply pressure condition to achieve 850 mbar suction pressure in their HAT facility. Hence, the introduction of heat exchanger helps to achieve the same suction pressure at 18 bar GN_2 supply pressure. It can be achieved by reducing the exhaust mass temperature from 450K to 380K and condensing 41 kg/s of steam out of 200 kg/s of steam by using the heat exchanger. The further multi-disciplinary investigations in the near future may reveal more advantages than the results presented at this point of time.

7. Conclusions

The ejector is used to maintain the vacuum and to avoid the backflow inside the test chamber. For this purpose, enormous amount of GN_2 is utilized by the ejector. The heat exchanger is introduced in between the ejector and isolation valve also it reduces the exhaust mass temperature and condenses some amount of steam. It reduces the total requirement of GN_2 and enhancing the performance of HAT facility. At present HAT facilities are having 4 cluster nozzles in the ejector system. By this investigation, 6 bar supply pressure will be saved per second in each nozzle for pumping out the secondary mass. As a result, 24 bar supply pressure is saved per second in the ejector system and the requirement of GN_2 is also reduced.

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