# Ejector Modeling and Examining of Possibility of Replacing Liquid Vacuum Pump in Vacuum Production Systems

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***Abstract*—In this study, ejector mathematical models have been presented based on thermodynamic relations governing it and in order to have an ejector computer simulation. The model which is developed based on integration equations momentum as well as energy for different parts of ejector, using special mathematical methods to solve and finally the results with real data for ejector system is assessed in vacuum distillation unit of Tehran refinery, proving that method has high accuracy. Also in continuation, in order to have a more comprehensive system review and to produce vacuum and do technical, economic comparison of the systems consisting of various vacuums: vacuum pumps, vacuum and ejector, their different arrangements were considered to combine an appropriate optimum of ejector and vacuum pump to reach a certain level of vacuum. Comprehensive study indicates that placement of a vacuum pump with ejector of third stage is more possible than the first and second stages of development. Since at least 5000 pounds per hour is reduced in the amount of steam consumed of ejectors (total of all three stages), the maximum ratio of return on investment (ROI) and the minimum initial investment will be needed.**

***Index Terms*— Ejector, modeling, mixing chamber, vacuum pump liquid.**

## I. Introduction

Ejectors are important equipment to produce vacuum and although have a relatively low efficiency, many industries and power plants use them to produce vacuum. Due to simple design and lack of moving parts in system, installation costs and a little maintenance is required and therefore is easily used is the industry. On the other hand, the major defects of ejectors, is large size versus their relatively little efficiency and production of noise pollution and high consumption of high pressure steam.

Several review articles to assess the full works have done in order to optimize the yield and consider the function of ejectors which have been published for example cunnanond and Emas [1] and Sun Aphornatana completely analyzed functionality of ejectors and those which have looked like sun and Emas [2], who have studied mathematical models for designing ejectors.

In this study, with attention to work done by previous researchers to evaluate and recognize ejectors, Different parts of ejector has been modeled and simulated with the computer analysis of production system of Tehran refinery vacuum in which ejector was used.

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## II. Theoritical

### *A. Ejectors and Its Function*

Structure of ejector is shown in Fig.1. Vacuum production takes place by the dynamic stimulus with high pressure, which is usually water steam. The basis, is the conversion of pressure energy into kinetic energy and vice versa in a way that the steam entering the high pressure nozzle reduced in level, also velocity and pressure increases until the nozzle throat quickly reaches the speed of sound passing through the throat and continuance to increase rapidly as the pressure finally reveals to the output at the end. We will see in the nozzle exit the highest speed and lowest pressure.

### *B. Ejector Modeling*

Since ejector modules, in HYSYS Software (and of course in all common process software) is not available and therefore for the simulation system, we can not use this software. So performance model has been proposed as an undeniable necessity. On this basis, with a comprehensive study of how ejector models developed in this field [3-5], finally general selection models were studied along with different parameters and they were combined together to developed a comprehensive and efficient model.

The assumptions of modeling are:

1) Driving steam drive is expanded in the nozzle as isentropic. Driving steam and vacuumed steam are also dense in isentropic.
2) Driving steam and vacuumed steam into the ejector is saturated and has a little speed.
3) The dense mixture speed which leaves ejector is very low.
4) Isentropic power is assumed constant.
5) Mixing of driving steam and vacuumed steam in the mixing chamber have been carried out at constant pressure.
6) Minor loss in efficiency of isentropic levels in mixing chamber has been considered low.
7) Ejector steam is mono-dimensional and assumed sustainable as well as adiabatic.
8) Equations are often assumed to show a complete behavior in the steam and gas.

For ideal gases considering the efficiency of nozzle, in an isentropic process we have the flowing relations:

$$\frac{P_1}{P_2}=\left[1+\frac{\gamma-1}{2\eta_n}.M^2\right]^{\frac{\gamma}{\gamma-1}} \quad (1)$$

$$\frac{T_1}{T_2}=1+\frac{\gamma-1}{2\eta_n}.M^2 \quad (2)$$

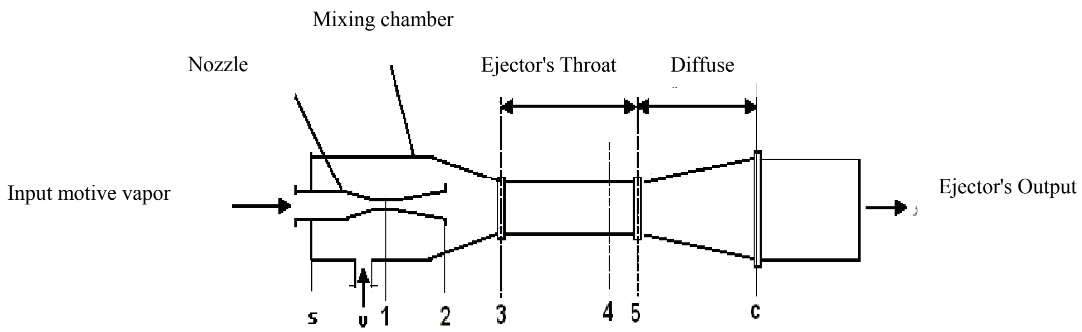


Fig. 1: Ejector And Its Structure

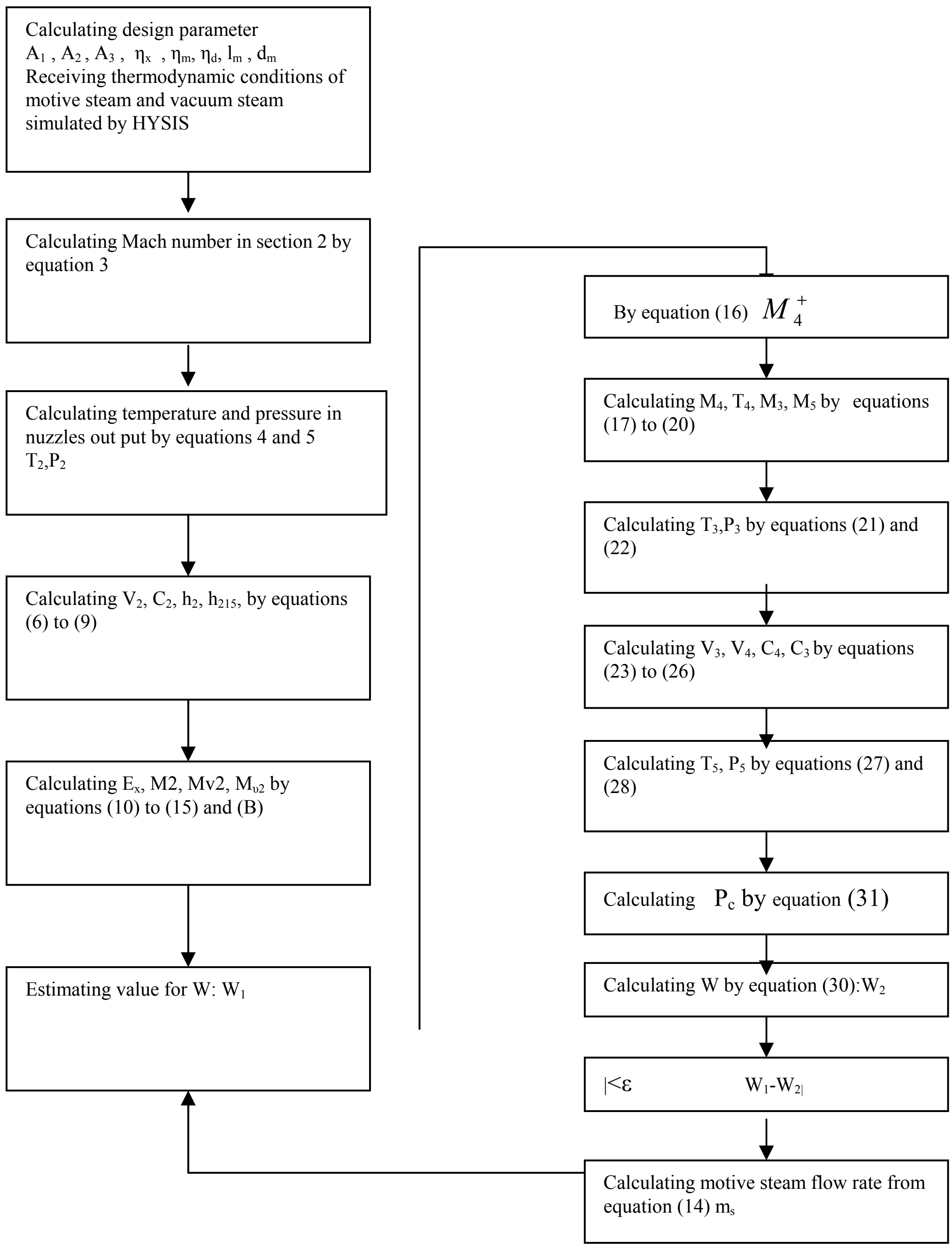


Fig.2: Algorithm For Simulation Of Ejector

Where, η is efficiency of nozzle. Through the modeling, Ejector is divided to three parts: Nozzle, mixing chamber and divider. Dominating relations on all three parts developed, so the proper algorithm finally achieved. Based on the above assumptions, the basic relations used in modeling of ejector, follows:

$$\frac{A_2}{A_1}=\sqrt{\frac{\left((\frac{2}{1+\gamma}).(1+\frac{\gamma-1}{2}.M_2^2)\right)^{\frac{\gamma+1}{\gamma-1}}}{M_2^2}} \quad (3)$$

Nozzle exit pressure (P2) that lowest pressure is hosted on ejector as it is calculated as follow:

$$P_2=\frac{P_s}{\left[\frac{\gamma-1}{2\eta_n}.M_2^2+1\right]^{\frac{\gamma}{\gamma-1}}} \quad (4)$$

To calculate the temperature of steam output stimulus:

$$T_2=\frac{T_s}{1+\frac{\gamma-1}{2\eta_n}\ .\ M_2^2} \quad (5)$$

Speed of sound in level 2 is the following:

$$C_2=\sqrt{\gamma.RT_2} \quad (6)$$

By finding the speed of sound in level 2, the actual flow rate at this stage is achieved as follows:

$$V_2=C_2 M_2 \quad (7)$$

Using the energy equation between input and output of nozzle, flow enthalpy in exit nozzle for isentropic process is achieved as follows [6]:

$$h_{2is}=h_s-\frac{V_2^2}{2\eta_n} \quad (8)$$

By using enthalpy of driving steam in exit nozzle for the process of isentropic and enthalpy of entrance driving steam enthalpy in exit nozzle is calculated in which vapor pressure is input by suction.

$$h_2=h_s-\eta_n(h_s-h_{2is}) \quad (9)$$

The vapor in the mixing chamber, the expansion process isentropic will get through. The expansion ratio is:

$$Er=\frac{P_s}{P_v} \quad (10)$$

Mach number of steam vacuum before mixing with driving steam nozzle is expressed as follows:

$$M_{v_2}=\sqrt{\frac{2}{\gamma-1}.\left[\left(\frac{P_v}{P_2}\right)^{\frac{\gamma-1}{\gamma}}-1\right]} \quad (11)$$

In general mode, to obtain the critical Mach number at any level, the following relationship can be used:

$$M_i^*=\sqrt{\frac{M_i^2(\gamma+1)}{M_i^2(\gamma-1)+2}} \quad (12)$$

Where considering equation (12), the critical Mach number in level 2 is achieved as follows:

$$M_2^*=\sqrt{\frac{M_2^2(\gamma+1)}{M_2^2(\gamma-1)+2}} \quad (13)$$

As defined, the ratio of suction is obtained as following:

$$w=\frac{m_v}{m_s} \quad (14)$$

Where, $m_v$ is suctioned steam flow rate and $m_s$ is driving steam flow rate.

Critical Mach number of driving steam output nozzle before mixing with sucking steam is achieved as follows:

$$M_{v_2}^*=\sqrt{\frac{M_{v_2}^2(\gamma+1)}{M_{v_2}^2(\gamma-1)+2}} \quad (15)$$

Mixing process with one-dimensional continuity equation combining movement and energy models and equations can be combined with the following relationships to calculate the critical Mach number and Mach number in level 4:

$$M_4^*=\frac{M_2^*+wM_{v_2}^*\sqrt{\frac{T_v}{T_s}}}{\sqrt{(1+w)\left(1+w.\frac{T_v}{T_s}\right)}} \quad (16)$$

$$M_4=\frac{\sqrt{2}.M_4^*}{\sqrt{(\gamma+1)-M_4^{*2}(\gamma-1)}} \quad (17)$$

The following relationship for calculating the temperature of mixed driving steam and suctioned steam before a shock is used [7]:

$$T_4=\frac{T_2}{1+\frac{\gamma-1}{2}.M_4^2} \quad (18)$$

The Mach number in sections 5 and 3 is:

$$M_5=\sqrt{\frac{M_4^2+\frac{2}{\gamma-1}}{\frac{2\gamma}{\gamma-1}.M_4^2-1}} \quad (19)$$

$$M_3=\sqrt{\frac{\frac{2}{\gamma-1}+M_5^2}{\frac{2\gamma}{\gamma-1}M_5^2-1}} \quad (20)$$

It is necessary to mention calculating the temperature and pressure in the third section, we use the following relations:

$$T_3=\frac{T_2}{1+\frac{\gamma-1}{2}.M_3^2} \quad (21)$$

$$P_3=\frac{P_2}{\left(1+\frac{\gamma-1}{2}M_3^2\right)^{\frac{\gamma}{\gamma-1}}} \quad (22)$$

Also the speed of sound and the actual flow rate in section 3 and 4 are obtained as:

$$C_3=\sqrt{\gamma.RT_3} \quad (23)$$

$$C_4 = \sqrt{\gamma . R T_4} \quad (24)$$

$$V_3 = C_3 \, M_3 \quad (25)$$

$$V_4 = C_4 \, M_4 \quad (26)$$

Temperature and pressure in the distributing input section is calculated as following [7]:

$$T_5 = \frac{1 + \frac{\gamma - 1}{2} . M_4^2}{1 + \frac{\gamma - 1}{2} . M_5^2} \quad (27)$$

$$P_5 = \frac{1 + \gamma M_4^2}{1 + \gamma M_5^2} . P_4 \quad (28)$$

Using the energy equation between sections 4 and 5 will have [6]:

$$V_5 = \left[ V_4^2 + \left( h_4 - h_5 \right) \right]^{\frac{1}{2}} \quad (29)$$

In order to calculate the output pressure of the distributor, we can use the following relations [7]

$$\frac{A_1}{A_3} = \frac{P_C}{P_s} . \left( \frac{1}{(1+w)\left(1 + w . \frac{T_v}{T_s}\right)} \right)^{\frac{1}{2}} . \frac{\left(\frac{P_2}{P_C}\right)^{\frac{1}{\gamma}} . \left(1 - \left(\frac{P_2}{P_C}\right)^{\frac{\gamma-1}{\gamma}}\right)^{\frac{1}{2}}}{\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} . \left(1 - \frac{2}{\gamma+1}\right)^{\frac{1}{2}}} \quad (30)$$

$$P_C = P_5 . \left( \eta_d . \frac{\gamma - 1}{2} . M_5^2 + 1 \right)^{\frac{\gamma}{\gamma - 1}} \quad (31)$$

Thus output flow rate of ejector is:

$$m_c = m_s + m_v \quad (32)$$

Based on the above equations, a complete set of governing relations in ejector exist which we can write algorithms for solving various problems in ejectors. In this study, we write a computer program and simulate the ejector.

### *C. Computational Algorithms*

The main goal of the simulation of ejector is calculation of driving steam consumption rate. In ejector simulation computing, physical features include cross ejector throat and nozzle exit cross section and constant level of ejectors and operational levels, including the stimulus temperature and vapor pressure, and temperature, pressure and flow of sucking steam and output pressure of ejector which are important. In Fig.2, an appropriate algorithm for simulation of ejector is presented.

### *D. Development of Computer Program*

Using the algorithm listed and object-oriented programming method a program for computer simulated ejector has been prepared, which is named VSS. Since for an accurate simulation of all equipment in the vacuum distillation unit, including vacuum systems and other equipment unit, the need for integrated simulation model and the model unit was VSS, therefore communication system (link) in connection HYSYS software and models providing a logical process and creating files between (Dynamic-Link Library) DLL of HYSYS with the main body of VSS, the output data from the distillation tower overhead into VSS model and output it back again to HYSYS. Note that the VSS software after simulated vacuum unit, vacuum pumps suitable for replacement with respect to the database (VSS and other economic calculations are related to these alternative systems done to finally optimize it for a specific user).

## III. Result And Discussion

### *A. Comparison of Results of VSS Software with Tehran Refinery Vacuum Production System*

The characteristics of Tehran refinery vacuum producing system are shown in Table 1. After compiling software VSS, software for simulation in a vacuum distillation unit is used in Tehran refinery that the results of the simulation system in vacuum distillation tower overhead units in north and south Tehran refinery are shown in Table 2.

As shown in Table 2, the relative error of this system is insignificant and therefore because of the accuracy of the software, it can be used to evaluate various parameters used in the unit.

### *B. Effect of Changes in the Second and Third Stages of Ejectors Capacity Consumption on Driving Steam of Their Priors' Ejectors*

For example, as seen in Fig.3, increasing of the suction capacity of second stage ejectors (due to reduced ejector first slot-loading time) causes the reduction of the steam consumption in ejector of first stage.

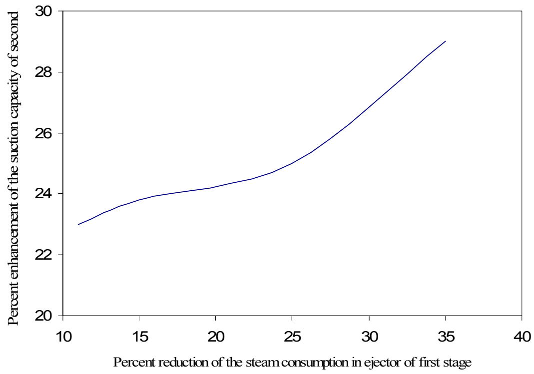


Fig.3: Increasing Of The Suction Capacity Of Second Stage Ejectors Causes The Reduction Of The Steam Consumption In Ejector Of First Stage.

### *C. Effect of Changes in Vacuum Production in Ejectors of Second and Third Stages On The Steam Consumption Of Their Pre-Stimulus Ejector*

As observed in Fig.4, increasing of vacuum production of ejectors in second stage (due to increased suction power of ejectors in first stage) reduces steam consumption in the first ejector.

### *D. Effect Of Changing Of The Vacuum On Steam Consumption Of Ejectors*

Fig.5 shows the effect of changing of the vacuum on steam consumption of steam vacuum tower ejectors. As mentioned in studies, the increase in vacuum level inside the tower increases overhead gas; therefore this increases the steam consumption of ejectors.

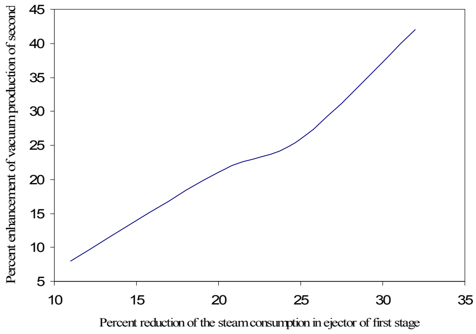


Fig.4. Increasing of Vacuum Production of Ejectors In Second Stage Reduces Steam Consumption in The First Ejector.

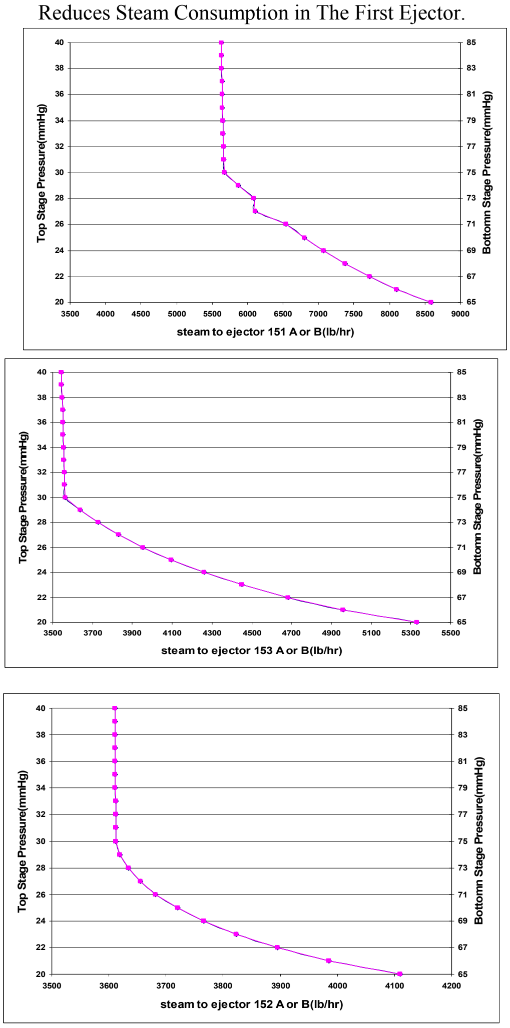


Fig.5: The Effect Of Changing Of The Vacuum On Steam Consumption Of Steam Vacuum Tower Ejectors.

### *E. Replacement Of Suitable Vacuum Pumps And Economic Calculation*

Considering ejector in the series in three stages in each stage three ejectors has been put parallel. The two are operating at anytime replacement of vacuum pump for each of three stages has been investigated and the results of the technical and economic evaluation are provided. For operation of information, processing in the wider and with more accuracy done, VSS software designed to define the technical and economic regulation of the vacuum pumps within the database (Data base) that, all technical and economic calculation are done by selecting any three step process, and reaching a level corresponding to the user and the results that are presented. These results in the technical sector include: possible replacement vacuum, steam consumption reduction of ejector in the same capacity and distribution and changes in operating conditions in the upstream stages. In the economic sector include: drawing ROI diagrams, expense, initial investment in terms of placement according to mode.

Summary results due to vacuum pump placement in each of three stages are as follows:

1) Consisting the capacity (suction flow) vacuum pump and vacuum production rate, a certain range of vacuum pumps and acceptable use of any Pump (although infinite number) is not possible.
2) Using a vacuum pump in each three-stage process, eliminates consider of that stage including, condensers are downstream. Also it must be noted that since the use of more pumps with higher capacities (or more vacuum production) may be possible therefore with each pump placement, the conditions will also change.
3) The comprehensive study shows that placement of a vacuum pump with ejector of third stage is possible higher than first and second stage of development. Since, at least 5000 pounds, while reducing the amount of steam consumed in ejector hours (total of three stages), than the maximum return on investment (ROI) and the minimum initial investment will be needed. In order to explain the reason this mode of placement, the Table 3 shows comparison of the number of pumps required for placement in any of three-stage.

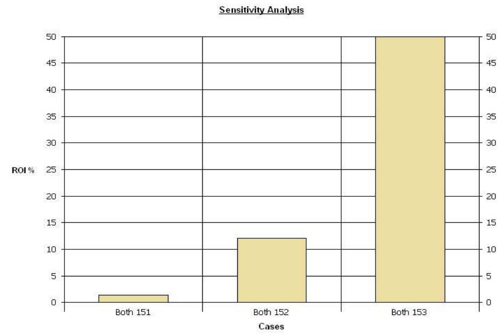


Fig.6: Comparison Of Percentage Return On Investment For Replacing Pump A In Different Modes With Ejectors Replacement In Three Stages.

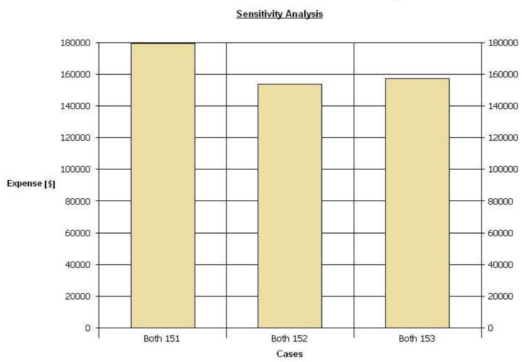


Fig.7: Comparison Of Costs For Pump "A" Of New System In Different Modes Replacement Of Ejectors Three Stages.

As Figs 6-8 show, the large number of pumps required in the first and second stages, while rejection of possible technical feasibility of situation causes this issue not to be economically affordable.

Table 4 shows the result of using ejectors in third step in different position.

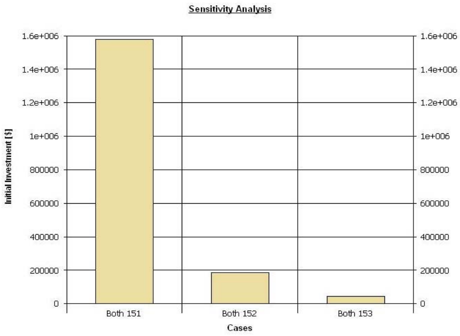


Fig.8: Comparison of The Initial Investment of Pump A In Different Modes of Replacement of Ejectors In Three Stages.

TABLE I: PROFILE OF SYSTEM SIMULATION

| *South vacuum production system* | | z | |
|---|---|---|---|
| *value* | Profile | value | Profile |
| *3* | Ejector step number | 3 | Ejector step number |
| *3* | Number of ejectors in every step | 3 | Number of ejectors in every step |
| *3* | Number of condensers | 3 | Number of condensers |
| *15696 Ib/hr* | Entering vapors flow rate to first step's ejectors | 15696 *Ib/hr* | Entering vapors flow rate to first step's ejectors |
| *Ib/hr 6050* | Entering vapors flow rate to second step's ejectors | *Ib/hr* 10697 | Entering vapors flow rate to second step's ejectors |
| *Ib/hr 5126* | Entering vapors flow rate to third step's ejectors | *Ib/hr* 8273 | Entering vapors flow rate to third step's ejectors |
| *1.9 Psia* | Exit pressure of first steps ejectors | 2.4 *Psia* | Exit pressure of first steps ejectors |
| *4.8 Psia* | Exit pressure of second steps ejectors | 4.8 *Psia* | Exit pressure of second steps ejectors |
| *15 Psia* | Exit pressure of third steps ejectors | 15.5 *Psia* | Exit pressure of third steps ejectors |
| *545* $^0F$ | Temperature of motive steam | 545 $^0F$ | Temperature of motive steam |
| *304.7 Psia* | *Pressure of motive steam* | *304.7 Psia* | *Pressure of motive steam* |

TABLE II: RESULTS OF UPSTREAM SIMULATION

| Vacuum distillation tower in north unit | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2EJ-153 A/B | | | 2EJ-152 A/B | | | 2EJ-151 A/B | | |
| steam () *Ib/hr* consumption rate | | Percent relative error | steam () *Ib/hr* consumption rate | | Percent relative error | steam () *Ib/hr* (consumption rate | | Percent relative error |
| simulation | design | | simulation | design | | simulation | design | |
| 3562 | 3560 | 0.05% | 3612 | 3651 | 0.08% | 5671 | 5600 | 1.26% |
| Vacuum distillation tower in south unit | | | | | | | | |
| EJ-153 A/B | | | EJ-152 A/B | | | EJ-151 A/B | | |
| 3981 | 3985 | 0.01% | 2985 | 2950 | 1.18% | 4835 | 4835 | %0 |

TABLE III: NUMBER OF PUMPS REQUIRED FOR PLACEMENT IN THREE STAGES

| Number of pump in third step | Number of pump in second step | Number of pump in first step | Production of vacuum (mbar) | Capacity ($m^3$/hr) | Pump name |
|---|---|---|---|---|---|
| - | - | 35 | 33 | 5950 | A |
| - | 4 | - | 120 | 10350 | A |
| 2 | - | - | 200 | 10150 | A |

TABLE IV: RESULT OF USING EJECTORS IN THIRD STEP IN DIFFEREN POSITION

| Percent reduction of steam consumption in the second stage ejector | Percent of changing of vacuum production of pump | percent of changing of pump capacity |
|---|---|---|
| 54 | +39 | +20 |
| 54 | +39 | +25 |
| 30 | +8 | +30 |

## IV. CONCLUSION

Ejectors are considered as equipment in the production of vacuum that are essential to know their behavior and performance in optimization of energy consumption in the vacuum units. In this study, ejector mathematical models have been presented based on thermodynamic relations governing it and in order to have an ejector computer simulation. The model which is developed based on integration equations momentum as well as energy for different parts of ejector, using special mathematical methods to solve and finally the results with real data for ejector system is assessed in vacuum distillation unit of Tehran refinery, proving that method has high accuracy. Also in continuation, in order to have a more comprehensive system review and to produce vacuum and do technical, economic comparison of the systems consisting of various vacuums: vacuum pumps, vacuum and ejector, their different arrangements were considered to combine an appropriate optimum of ejector and vacuum pump to reach a certain level of vacuum. Comprehensive study indicates that placement of a vacuum pump with ejector of third stage is more possible than the first and second stages of development. Since at least 5000 pounds per hour is reduced in the amount of steam consumed of ejectors (total of all three stages), the maximum ratio of return on investment (ROI) and the minimum initial investment will be needed.

## NOMENCLATURE AND SYMBOLES

| | |
|---|---|
| A | Section area ($m^2$) |
| $C_p$ | Specific heat capacity ($\frac{kj}{kg.K}$) |
| Cr | Contraction rate |
| d | Diameter (m) |
| $Er$ | Expansion rate |
| h | Enthalpy ($\frac{kj}{kg}$) |
| $l$ | Length (m) |
| m | Mass flow rate (kg/s) |
| M | Much number |
| $M^*$ | Critical Much number |
| P | Pressure (kpa) |
| T | Temperature (K) |
| V | Velocity (m/s) |
| $v$ | Specific volume ($\frac{m^3}{kg}$) |
| $w$ | Suction rate |
| $\eta$ | Yield |
| $\gamma$ | Specific heat capacity rate |

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