Non Isentropic Performance of Supersonic Separators

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Abstract
Supersonic separator (3S) provides submicron separation of liquids from gas streams. The advanced separation is based on adiabatic gas expansion due to attaining supersonic velocities accompanied with creation of huge centrifugal acceleration (500,000g) which is very adequate for separation of water or hydrocarbon condensates from natural gas. Most of the previous works have been assumed isentropic operation. In this article, the effect of process non-isentropicity is investigated on 3S performance. Modeling of 3S is studied using three different approaches: a) the entire system is viewed as an isentropic process, b) isentropic expansion and contraction in nozzle diffuser accompanied with non isentropic shock wave, c) the entire system is viewed as a non-isentropic process. The simulation results clearly indicate that the process nonisentropicity causes a pre-mature shock occurrence. Evidently, the non-isentropic fluid temperature is higher than the isentropic case which leads to lower liquid collection due to less condensation. Hence, total separation efficiency will be decreased in the presence of process nonisentropicity. Furthermore, the effect of various back pressures in three above cases are compared together and it is shown that the process nonisentropicity reduces overall pressure recovery.

Keywords: *Supersonic separator (3S), Shock wave, nonisentropicity, modeling, simulation*

1. Introduction
In recent years a novel and advanced technology with the name of supersonic separator is existed in oil and gas industries. A very small extent, easy moving possibility of unit, increasing of separation yield, comply with environmental regulations, are only some of 3S advantages. Also, this process capable to eliminate selective water and heavy hydrocarbons from natural gas streams in high relatively pressure [1-4]. This separator enable to separation of liquid droplets about sub micron. Fig.1 shows the interior structure of 3S.

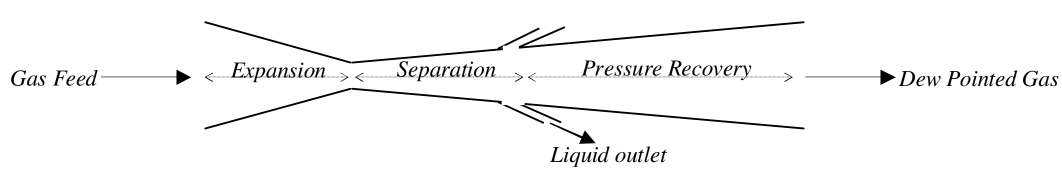


Fig.1- Interior structure of 3S

The gas enters with a low velocity (10-50 m/s) and high pressure (30-100 atm) to the entrance section of 3S. With passing of the gas from nozzle-diffuser segment the gas velocity is

increased more than 700 m/s (Ma>1.4) due to transforming of potential energy to kinetic energy. As a result of Joule-Thomson effect, gas temperature is decreased and water and heavy hydrocarbons are considerable condensed in natural gas. Under the excessive centrifugal acceleration about 300,000-500,000g (created by special vanes), the liquid droplets are thrown away towards the diffuser wall, leaving the 3S by a circumferential passage [5,6]. After this point, the fluid should be slowed dawn for pressure (and temperature) recovery reasons. This task can be achieved by using normal shock wave.
In the present work, modeling of three different cases (isentropic process, non isentropic process, and isentropic process accompanied with non isentropic shock wave) are considered upon 3S performance. The obtained simulation results are compared with each other and the effect of various back pressures are also investigated on 3S separation efficiency. This study can be applied as a useful tool for investigating the flow behavior and position of normal shockwave occurrence in 3S separators under different operating conditions.

2. Mathematical model of the supersonic separator

Three approaches below are considered in mathematical modeling of 3S:

- *The entire process in terms of isentropic*
- *Isentropic process accompanied with non isentropic normal shock wave*
- *The entire process in terms of nonisentropic*

2.1. Isentropic Process modeling

Friction effects and energy losses of the system are ignored in this modeling section.

2.1.1. Mathematical model of the converging part of the nozzle

Eqs.1 to 5 are derived for one dimensional, isentropic and steady state flow in converging nozzle part. The indices 'i' and 't' indicate inlet and throat fluid flow conditions, respectively.

$$A_t = A_i\left(\frac{\rho_i}{\rho_t}\right)\left(\frac{V_i}{V_t}\right) \qquad \text{Continuity equation} \quad (1)$$

$$\left(\frac{T_i}{T_t}\right) = \left(\frac{\rho_i}{\rho_t}\right)^{k-1} = \left(\frac{P_i}{P_t}\right)^{\frac{k-1}{k}} \qquad \text{Polytrophic process} \quad (2)$$

$$C_t = V_t = \sqrt{\frac{dP}{d\rho}} = \sqrt{kRT_t} \qquad \text{Momentum \& continuity equations} \quad (3)$$

$$V_t^{\,2} = \left[V_i^{\,2} + \frac{2k}{k-1}[\,RT_i - RT_t\,]\right] \qquad \text{Energy equation} \quad (4)$$

$$x_t = \left(\frac{A_i^{0.5} - A_t^{0.5}}{\pi^{0.5}\tan(\alpha)}\right) \qquad \text{Geometrical consideration} \quad (5)$$

For a given converging nozzle angle (α), simultaneous solution of the above 5 non-linear equations provides all required parameters (T_t, P_t, A_t, x_t, V_t)at the throat conditions.

2.1.2. Mathematical model from throat to shock front

Similarly, eqs. (6) to (10) can be used to depict the isentropic one dimensional flow of an ideal gas inside a diverging nozzle from throat to normal shock front .The index 'bs' indicates the flow conditions before normal shock occurrence.

$$A_{bs} = A_t \left(\frac{\rho_t}{\rho_{bs}}\right)\left(\frac{V_t}{V_{bs}}\right) \quad (6)$$

$$\left(\frac{T_t}{T_{bs}}\right) = \left(\frac{\rho_t}{\rho_{bs}}\right)^{k-1} = \left(\frac{P_t}{P_{bs}}\right)^{\frac{k-1}{k}} \quad (7)$$

$$C_{bs} = \sqrt{kRT_{bs}} \quad (8)$$

$$V_{bs}^2 = \left[V_t^2 + \frac{2k}{k-1}[RT_t - RT_{bs}]\right] \quad (9)$$

For a given diverging nozzle angle (β), the distance between throat and shock wave location can be computed using the following equation:

$$x_{bs} = \left(\frac{A_{bs}^{0.5} - A_t^{0.5}}{\pi^{0.5}\ tan(\beta)}\right) \quad (10)$$

2.1.3. Mathematical model for two side of normal shock wave (before and after shock)

Eqs. (11) to (14) describe the isentropic, one dimensional flow of the gas passing through the normal shockwave.The index 'as' indicates the flow conditions after normal shock occurrence.

$$\rho_{bs}V_{bs} = \rho_{as}V_{as} \Rightarrow V_{bs}\frac{P_{bs}}{RT_{bs}} = V_{as}\frac{P_{as}}{RT_{as}} \quad (11)$$

$$P_{bs} + \rho_{bs}V_{bs}^2 = P_{as} + \rho_{as}V_{as}^2 \quad (12)$$

$$Cp_{bs}T_{bs} + \frac{V_{bs}}{2} = Cp_{as}T_{as} + \frac{V_{as}}{2} \quad (13)$$

$$C_{as} = \sqrt{kRT_{as}} \quad (14)$$

2.1.4. Mathematical model from normal shock to exit conditions

Equations (15) to (20) describe the isentropic, one dimensional flow of an ideal gas in the nozzle diverging part between shockwave to exit. The index 'e' indicates exit fluid conditions.

$$A_e = A_{as}\left(\frac{\rho_{as}}{\rho_e}\right)\left(\frac{V_{as}}{V_e}\right) \quad (15)$$

$$\left(\frac{T_e}{T_{as}}\right) == \left(\frac{P_e}{P_{as}}\right)^{\frac{k-1}{k}} \quad (16)$$

$$C_e = \sqrt{kRT_e} \quad (17)$$

$$V_e^2 = \left[V_{as}^2 + \frac{2k}{k-1}[RT_{as} - RT_e]\right] \quad (18)$$

The distance between shockwave and nozzle exit can be computed using following equation:

$$x_{as} = \frac{A_e^{0.5} - A_{as}^{0.5}}{\pi^{0.5}\ tan(\beta)} \quad (19)$$

With simultaneous solution of non-linear eqs. (6-19) all required parameters from throat to exit location can be calculated.

2.2. Modeling of isentropic process accompanied by non isentropic normal shock wave

Shock phenomenon has crucial effect on 3S performance. Hence, energy loss due to normal shock wave is only considered in this section and rest of the process will be same as isentropic state. Equations (20) to (22) describe the non isentropic, one dimensional flow of an ideal gas between two sides of the shock wave.

$$P_{as} - P_{bs} = m(V_{bs} - V_{as}) \qquad \textit{Hugoniot equation} \quad (20)$$

$$m = \rho_{bs} C_{bs} \sqrt{1 + \frac{k+1}{2k} \frac{P_{as} - P_{bs}}{P_{bs}}}$$

Where, 'm' is mass flux, that passing from shock wave.

$$m = \rho_{bs} V_{bs} \Rightarrow P_{as} = P_{bs} \left[1 + \frac{2k}{k+1} \left(Ma_{bs}^{2} - 1 \right) \right] \qquad (21)$$

$$\rho_{bs} V_{bs} = \rho_{as} V_{as} \Rightarrow V_{bs} \frac{P_{bs}}{RT_{bs}} = V_{as} \frac{P_{as}}{RT_{as}} \qquad (22)$$

2.3. Non isentropic Process modeling

In this section, two kind of energy loss terms are considered as follows:

- *Energy loss due to friction effect in 3S (skim friction)*
- *Energy loss due to normal shock wave (form friction)*

Whereas friction term is only appeared in energy equation, therefore, this equation is differed from isentropic energy equation. Other equations are the same as isentropic state and parameter 'n' (polytropic exponent) is only substituted instead of parameter 'k' for describing nonisentropic process. In this case, the energy equation is in terms of below:

$$v_{post}^{2} = \frac{v_{pre}^{2} + \frac{2n}{n-1}\left[RT_{pre} - RT_{post}\right]}{1 + G_c f} \qquad (23)$$

Where f is faning friction coefficient and G_c is geometric factor. 'pre' and 'post' indexes are relating to the primary and terminal conditions in each part of 3S, respectively. The equations of section 2.2 are applied for modeling of non isentropic shock wave.

3. Simulation results and discussion

Figures 2 to 6 show pressure, temperature, velocity, sonic velocity and much number profiles for three different cases as mentioned above.

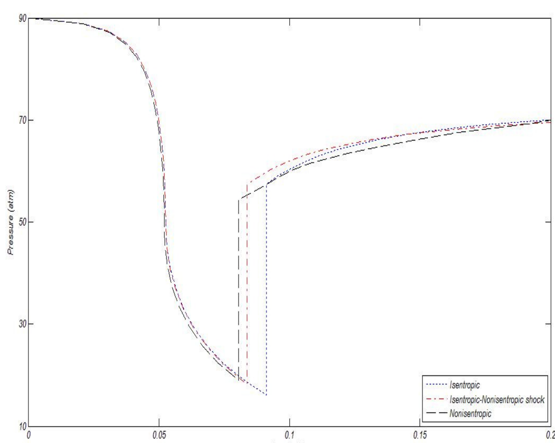


Fig.2. Pressure profiles at nozzle for exit pressure (70 atm)

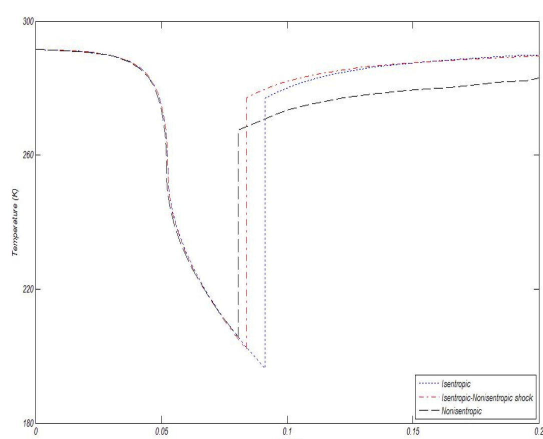
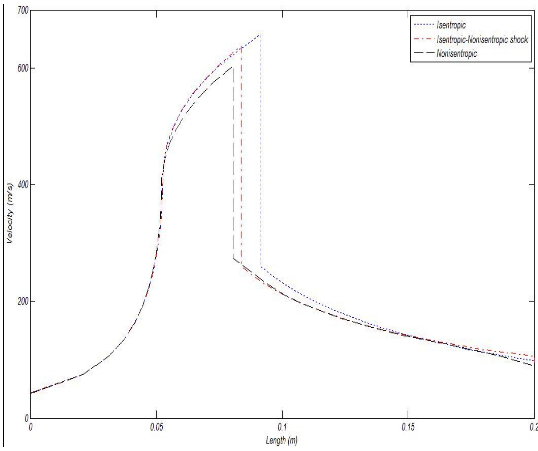


Fig.3. Temperature profiles at nozzle for exit pressure(70 atm)



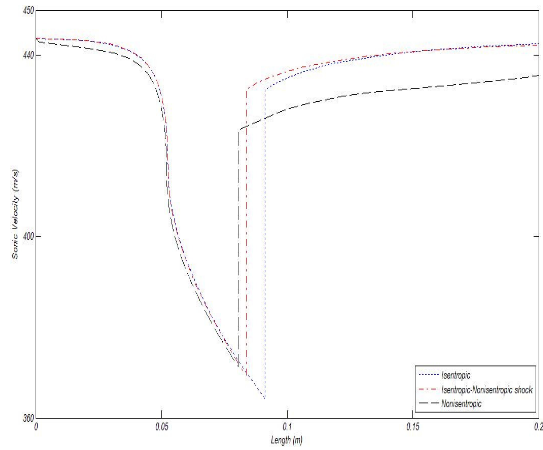
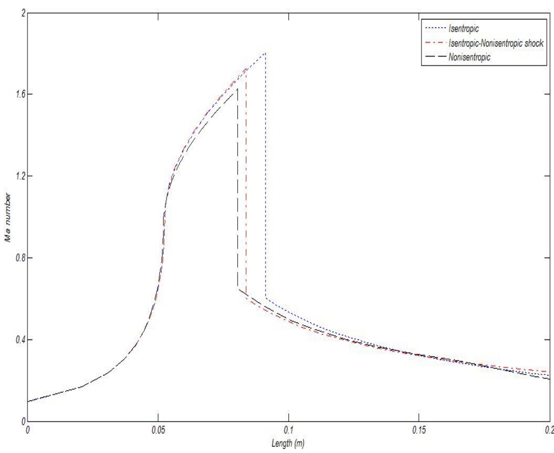


Fig.4.Velocity profiles at nozzle for exit pressure (70 atm) ***Fig.5. Sonic velocity profiles at nozzle for exit pressure(70 atm)***



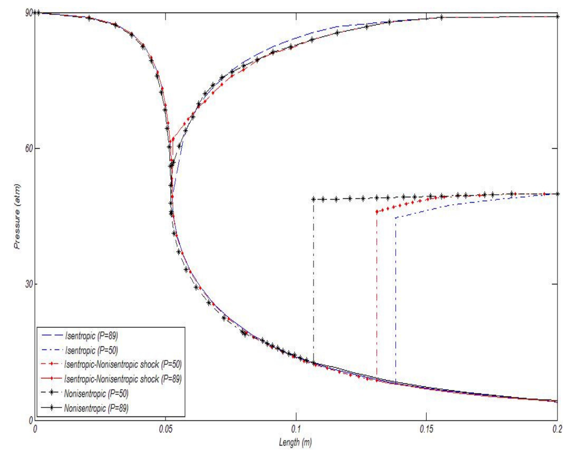
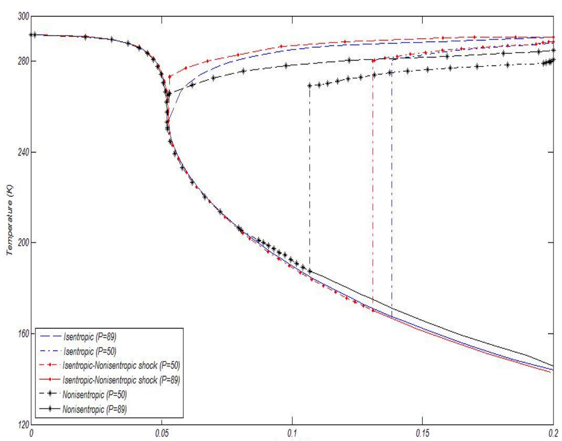


Fig.6. Mach num. profiles at nozzle for exit pressure (70 atm) ***Fig.7. Pressure profiles at different exit pressures***



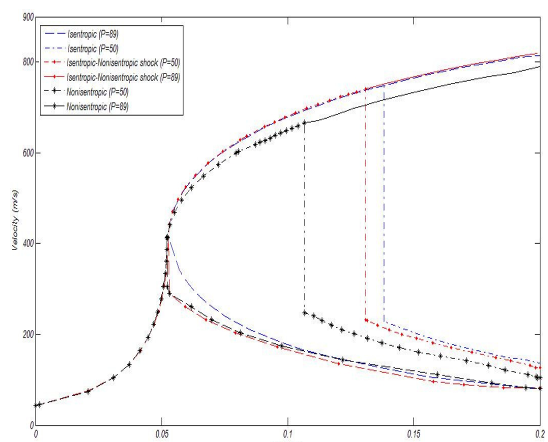


Fig.8. Temperature profiles at different exit pressures ***Fig.9. Velocity profiles at different exit pressures***

As it can be seen, non isentropicity causes that shock phenomenon occurs earlier. In other words, shock wave is more closed to the throat, and as the process becomes more non isentropic, the shock wave approaches to throat position. In fact, non isentropicity is caused that less potential energy is transformed to the kinetic energy in before shockwave location.

Clearly, fluid temperature in non-isentropic process is higher than the isentropic process. Whereof the amount of condensed liquid is considerably a function of fluid temperature, Hence, total separation efficiency will be decreased in the presence of process nonisentropicity due to less condensation.

As shown in figures, non isentropic state profiles is lied below the other profiles. This situation is more noticeable in diverging part of the nozzle. This reality is due to friction effects. Because the length of diverging part is more longer than converging segment, so more friction energy losses is existed in this part of separator.

All simulations for comparing three different approaches of modeling were done in constant back pressure (70 atm). Back pressure in 3S has profound effect on normal shock wave location, so in figures 7 to 9 various back pressures effect were compared together in three status of performed modeling. With decreasing of back pressure, shock wave location is moved toward nozzle exit and energy losses due to shockwave and friction will be more. As a consequence, the process nonisentropicity reduces overall pressure recovery.

4. Conclusion

Modeling of 3S separator has been performed under various assumptions and different process operating conditions (such as backpressures). the simulation results could be used as a proper tool for design, scale-up and control studies of 3S separation processes. The obtained results showed that nonisentropicity has noticeable effect upon separation performance which ignoring this effect can lead to appreciable errors in 3S design and operation. As energy losses increases due to nonisentropicity, the shock wave becomes closer to the throat and gas cooling is lowered. As a result, total separation efficiency will be decreased. In isentropic processes more pressure recovery will be achieved in 3S exit for a fixed entrance pressure. On the other hand, in non isentropic processes (as in real situations) more pressure losses will be encountered.The simulation results revealed that by decreasing the back pressure, losses due to skin and form frictions will be increased due to larger normal shock occurrence. Evidently, non isentropic case can explain more realistic predictions for fluid behavior across the 3S separator.

5. References

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