# A Method for Prediction of Gas/Gas Ejector Performance

A correlation for ejector efficiency with accuracy range ±2% was found between the model and published results. From this, a methodology was established to determine ejector performance at a conceptual level, using commercial cfd simulation software

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Experience during the execution of engineering design and consultancy services has shown that the commonly available process simulation software is not applicable for many gas/gas ejector applications encountered. Gas ejector design can however be determined by rigorous calculation using the applicable equations [1, 2].
A study was performed to establish a simpler methodology for ejector design and for the prediction of performance, based on the following:

- published results by manufacturers;
- literature survey;
- published empirical results;
- experience from design projects.

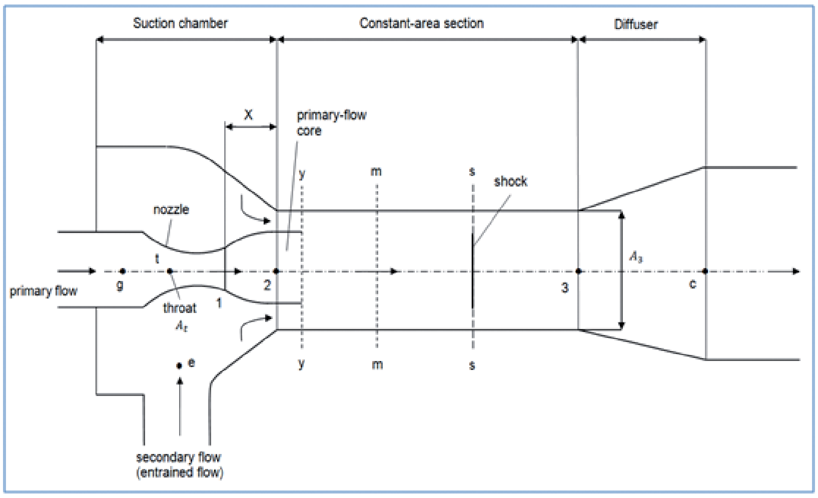



Fig. 1 - Sketch of gas/gas ejector based on [1, 2]

A thermodynamic spreadsheet model was prepared based on equations [1, 2]. Results were analyzed and compared with published results and with the simulation results obtained by using cfd codes (as UNISIM and HYSIS). Findings are presented herein, together with a recommended simplified method for the prediction of ejector performance.

## Ejector performance analysis

**Figure 1** shows a sketch of gas/gas ejector based on [1, 2]. The applicable equations are provided by Huang et al [1, 2] as follows:

- primary flow (active gas) through nozzle: The HP (active) gas is accelerated to sonic velocity in the throat of the ejector inlet nozzle

$$\dot{m}_p = \frac{P_g A_t}{\sqrt{T_g}} \times \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{(\gamma+1)}{(\gamma-1)}}}\sqrt{\eta_p} \qquad (1)$$

- pressure and Mach number at nozzle exit plane (depends on area at exit of throat)

$$\left(\frac{A_{p1}}{A_t}\right)^2 \approx \frac{1}{M_{p1}^2}\left[\frac{2}{\gamma+1}\left(1+\frac{(\gamma-1)}{2}M_{p1}^2\right)\right]^{\frac{(\gamma+1)}{(\gamma-1)}} \qquad (2)$$

$$\frac{P_g}{P_{p1}} \approx \left(1+\frac{(\gamma-1)}{2}M_{p1}^2\right)^{\frac{\gamma}{(\gamma-1)}} \qquad (3)$$

Equation 3, however, does not account of the

## Nomenclature

| | |
|---|---|
| $a_1, a_2, c_1, c_2, c_3$ | Coefficients |
| A | Area |
| M | Mach number |
| $\tilde{m}$ | Mass flow rate |
| n | Value of Cp / Cv adjusted for isentropic efficiency |
| Pe | Vapour pressure at the suction port of the ejector (passive gas) |
| Pg | Vapour pressure at the nozzle inlet of the ejector (active gas) |
| PR | Pressure ratio $P_g/P_e$ |
| R | Gas constant |
| T | Temperature |
| V | Gas velocity |
| $\gamma$ | Cp / Cv |
| $\phi_m$ | Mixing coefficient |
| $\eta$ | Isentropic efficiency |
| $\eta_p$ | Isentropic efficiency – primary (active) flow through nozzle |
| $\eta_m$ | Isentropic efficiency – flow through diffuser |
| $\varpi$ | Entrainment ratio = $m_s$ / $m_p$ |
| Subscripts | |
| c | Exit of ejector |
| e | Inlet port of the entrained flow (passive gas) |
| g | Nozzle inlet, active gas |
| m | Mixed flow |
| p | Primary (active) flow |
| pl | Nozzle exit |
| py | Primary flow at the location of choking for the entrained flow |
| s | Suction or entrained flow, passive gas |
| sy | Entrained flow at the location of choking for the entrained flow |
| t | Nozzle throat |
| y-y | Plane of ejector cross section at the commencement of mixing section |
| 1 | Nozzle exit |
| 2 | Entrance of the constant-area section |
| 3 | Exit of the constant-area section |

isentropic efficiency. Therefore the following adjustment is made:

$$\eta = \frac{\left(\frac{P_2}{P_1}\right)^{\frac{(\gamma-1)}{\gamma}} - 1}{\left(\frac{P_2}{P_1}\right)^{\frac{(n-1)}{n}} - 1} \qquad (4)$$

Secondary flow (passive gas) through nozzle:

$$\frac{P_e}{P_{sy}} \approx \left(1 + \frac{(\gamma-1)}{2} M_{sy}{}^2\right)^{\frac{\gamma}{(\gamma-1)}} \qquad (5)$$

The pressure at cross section y-y is required to be lower than that of the passive gas, to ensure sufficient passive gas flow. As the design entrainment ratio increases, the design area for passive gas flow will be increased. Nevertheless, passive gas velocity will be required to increase, thus the pressure at y-y will be required to decrease. The following equations describe the mixing process downstream of the nozzle:

- momentum balance

$$\phi_m\left[\dot{m}_p V_{py} + \dot{m}_s V_{sy}\right] = (\dot{m}_p + \dot{m}_s) V_m \quad (6)$$

- energy balance

$$\dot{m}_p\left(C_{p,py}T_{py} + \frac{V_{py}^{\ 2}}{2}\right) + \dot{m}_s\left(C_{p,sy}T_{sy} + \frac{V_{sy}^{\ 2}}{2}\right) = (\dot{m}_p + \dot{m}_s)\left(C_{p,m}T_m + \frac{V_m^{\ 2}}{2}\right) \quad (7)$$

Prior to entering the diffuser, the mixed gas velocity reduces to less than sonic velocity, consequently a shock wave is generated. The pressure ratio and Mach number of the gas downstream of the shock wave are calculated as follows:

$$\frac{P_3}{P_m} = 1 + \frac{2\gamma}{\gamma+1}\left(M_m^{\ 2} - 1\right) \quad (8)$$

$$M_3^{\ 2} = \frac{1 + \frac{(\gamma-1)}{2} M_m^{\ 2}}{\gamma M_m^{\ 2} - \frac{(\gamma-1)}{2}} \quad (9)$$

The pressure increase across subsonic diffuser can then be calculated by:

$$\frac{P_c}{P_3} \sim \left(1 + \frac{(\gamma-1)}{2} M_3^{\ 2}\right)^{\frac{\gamma}{(\gamma-1)}} \quad (10)$$

Equation 10, however, does not account of the isentropic efficiency. Therefore the adjustment in equation 4 was made.
Results for operating offshore ejectors located in the Hewlett Field (Rottlegendes and Zechstein) were obtained from Sashar et al. [3, 4].
The recommended isentropic efficiencies for the primary flow (active gas) though the ejector nozzle and for the mixed flow though the ejector diffuser are 95% and 85% respectively [1, 2].
The following correlation was derived for the mixing coefficient based on information provided by Huang et al. [3, 4]:

$$\phi_m = a_1 - a_2 * A_3/At \quad (11)$$

# Method of analysis

The requirements for successful completion of an energy balance over the ejector are discussed in the paragraph below. It becomes quickly apparent that such an energy balance cannot be performed with currently available process simulation models. As can be seen from the equations above, an increase in entrainment ratio requires a reduction in the value of $P_y$ to provide sufficient driving force to accelerate the passive gas. As a result, a larger conversion of pressure into kinetic energy and then kinetic energy back to pressure occurs. Since efficiency losses occur in both the expansion and compression steps, the total energy losses increase. Energy losses due to the momentum balance during mixing of the active and passive stream as well as friction losses are also expected to increase as the entrainment ratio increases. Currently available process simulation software does not provide the facility to estimate the value of $P_y$ required.
As previously stated, a thermodynamic spreadsheet model was prepared using the equations presented above from [1, 2] to determine the velocities, pressures, temperatures and energy balance for a gas/gas ejector. The results obtained were then compared with values quoted in the references.
Energy balances for the calculation of isentropic efficiencies were performed by inputting the above results into cfd simulations. Both the active and the passive gas used were natural gas.

# Results and discussion

The discharge pressures – as a percentage of the active gas pressure - obtained by the thermodynamic model from equations by Huang

Table 1 - Comparison of results of thermodynamic spreadsheet model with literature references

| Active gas / Passive gas pressure ratio | 1.5 | 1.5 | 1.5 | 2 | 2 | 2 | 3 | 3 | 3 |
|---|---|---|---|---|---|---|---|---|---|
| Entrainment ratio | 0.1 | 0.5 | 1.0 | 0.1 | 0.5 | 1.0 | 0.1 | 1.0 | 2.0 |
| Discharge pressure / Active gas pressure (%) [4] kPA (abs) | 86 | 76 | 71 | 76 | 64 | 58 | 61 | 42 | 37 |
| Discharge pressure / Active gas pressure (%) Thermodynamic model [1, 2] kPA (abs) | 84 | 75 | 69 | 80 | 65 | 57 | 67 | 43 | 35 |

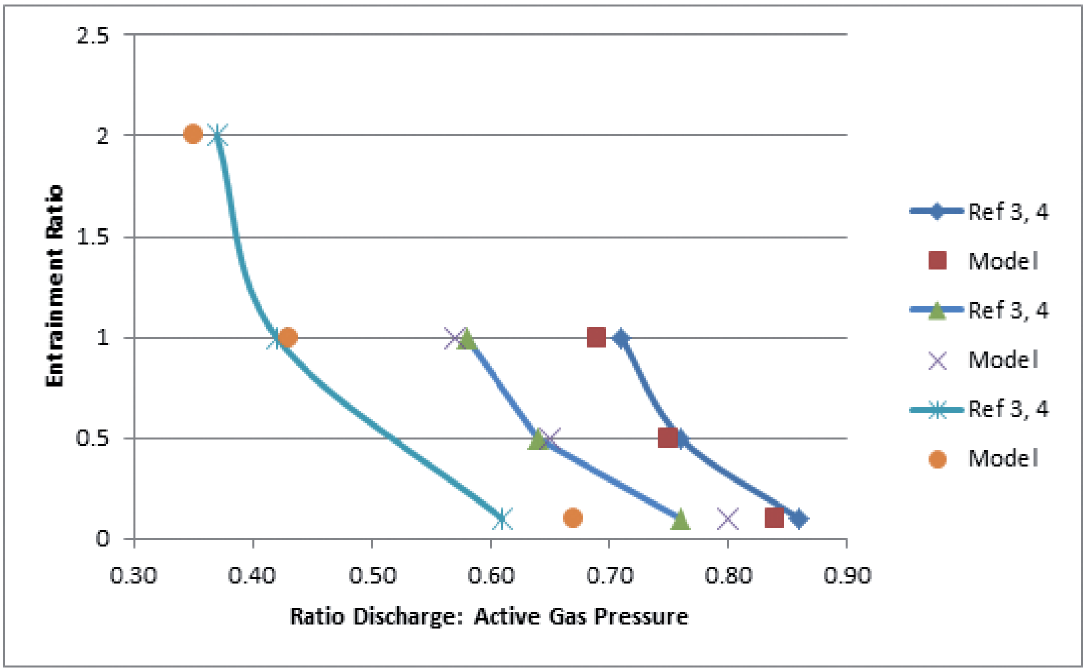



Fig. 2 - Comparison of discharge pressure results for thermodynamic model based on equations in [1, 2] and discharge pressures from [3, 4]

[1, 2] are compared with results by Sashar [3, 4] in **table 1**. Results are also plotted in **figure 2**.

As can be seen, there is a good correlation between the two sets of results over the following ranges: entrainment ratio 0.1 – 1.0; active to passive gas pressure ratio 1.5 – 3.0. A possible reason for the small differences between the two sets of results is that the model uses equation 11 to calculate $\Phi_m$, whereas the ejector supplier has proprietary knowledge of mixing factors $\Phi_m$. Supplier results [3, 4] are based on supplier knowledge of ejector design and were therefore utilized in further calculations and analysis.

Cfd process simulations were performed as shown in **figure 3**. No allowance was made in the simulation models for friction and momentum losses. The efficiencies shown in the graph (below were calculated as power input to the expander (88% isentropic efficiency [1]) divided by the power output at the inlet nozzle (95% isentropic efficiency [1]).

Resulting values of  are plotted in **figure 4** and reflect the following:

- friction and momentum losses;
- slipping and viscous effect;
- losses due to non-ideal isentropic behavior during acceleration of the passive gas;
- isentropic losses due to reduced pressure in the mixing section to enable entrainment of passive gas.

A generalized correlation of the above relationships was obtained using an equation with the following form

$$\eta_U = 0.382 * P_e/P_g + 0.47 + (0.619/P_g + 0.0312) \cdot \varpi \quad (12)$$

The results of the above correlation equation are compared with literature results [3, 4] in **figure 5**.

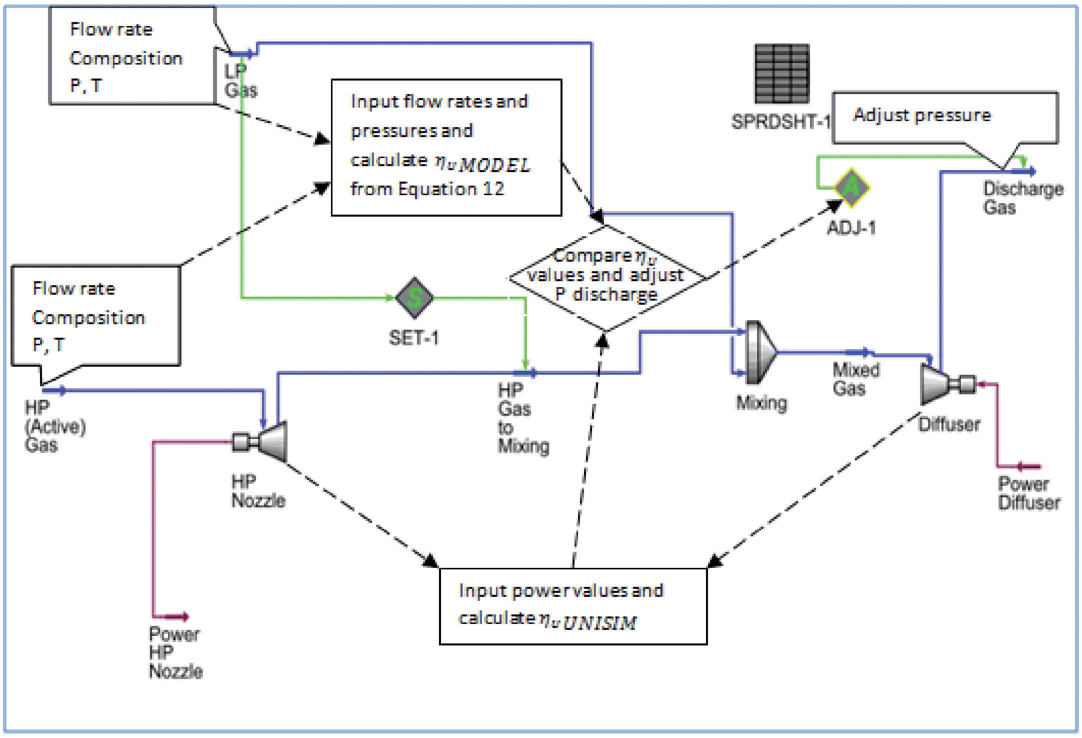
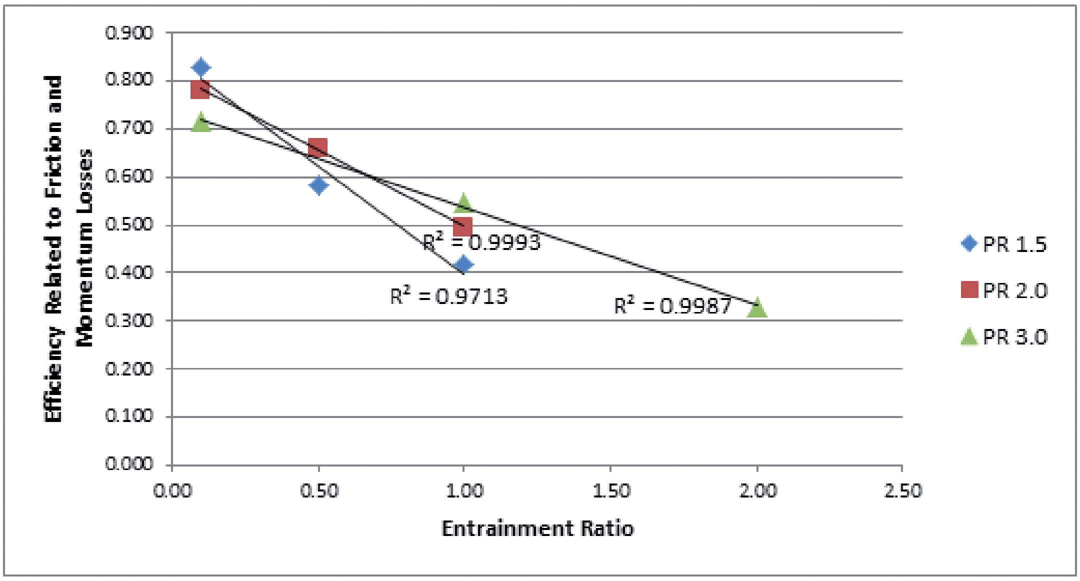



Fig. 3 - Schematic of cfd process simulation

Fig. 4 - Efficiencies (results versus entrainment ratio based on [3, 4] for various active / passive gas pressure ratios




Results for operating units [3, 4] are also plotted. As can be seen the correlation provides a good fit to all results.

A cfd model for easy use in simulating gas/gas ejectors was prepared as follows (figure 3):

- the ejector nozzle expansion chamber is simulated as a turbo expander with isentropic efficiency 95%;
- the diffuser is simulated as a centrifugal compressor with isentropic efficiency 88%;
- a a tool of the used cfd code calculates friction/momentum efficiency based on the pressure ratio and entrainment ratio; the tool then adjusts the gas discharge pressure until this efficiency is met.

## Conclusion

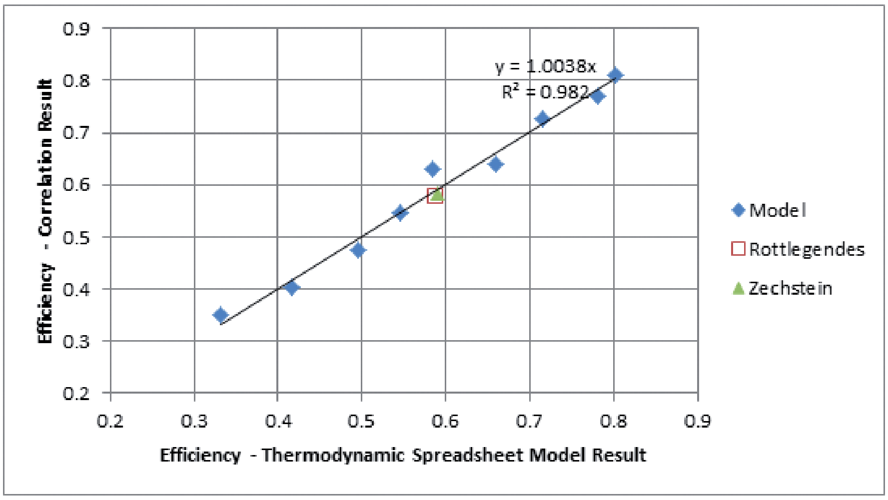
A key practical criterion for gas/gas ejector performance is the discharge gas pressures achieved for specific active and passive gas pressures and entrainment ratios. In this respect, thermodynamic model results for natural gas present a close approximation of gas/gas ejector performance for the following ranges:

- entrainment ratio 0 to 2;
- pressure ratio (PR) 1.5 to 3;
- molecular weight 17 – 20;
- active gas pressure 10 - 100 barg;
- the related natural gas physical properties.

This approximation can be improved further by the input of more accurate values of mixing factors $\Phi_m$ derived from literature results.

A methodology is demonstrated above for prediction of ejector performance using commercial cfd simulation software. Based on results above, this method is accurate to within 2% with respect to the energy balance and the gas discharge pressure. This methodology may be used as a conceptual tool. It is not proposed that it should be used for detailed engineering, where supplier specialized knowledge is required.

Fig. 5 - Efficiencies from correlation equation of versus model results based on [3, 4] for active / passive gas pressure ratios 1.5 to 3.0

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# Metodo per prevedere le prestazione di un eiettore gas/gas

I software disponibili per la simulazione di processo non sono applicabili su molti dei casi di eiettori gas/gas incontrati nella tecnica. Pertanto, è stato considerato opportuno effettuare uno studio per definire una semplice metodologia di progettazione dell'eiettore e per predirne le prestazioni. Lo studio si basa su informazioni pubblicamente disponibili e sull'esperienza maturata in progetti applicati.
Le equazioni applicabili sono state elaborate mediante un modello termodinamico. I risultati del modello, prodotti per un range di rapporti di pressione gas attivo/gas passivo e di rapporti di trascinamento, sono stati analizzati e confrontati con dati disponibili in letteratura e con i risultati di simulazione condotta mediante codici cfd commerciali (UNISIM e HYSIS). È stata trovata una correlazione, con accuratezza di ±2%, tra i dati del modello e i risultati pubblicati. Da questa è stata ricavata una metodologia per determinare, a livello preliminare, le prestazioni dell'eiettore mediante codici di simulazione cfd.