Theoretical and experimental features of the thermodynamic process in oil injection screw compressors

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Abstract. For optimum performance of screw compressors, reduce wear and improve leakage, oil injection needs to be applied. The injected oil runs through the compressor together with the gas, taking a part of the heat of the gas resulting from compression during the process. The paper presents a theoretical analysis of the compression process affected by the cooling of the oil injection. The oil injection screw compressor is ideal for this process because the oil injected into the compressor along with the lubrication and sealing technology cools the compressed gas, which makes the compression process to be much closer to an isothermal process (minimum compression required). In order to calculate the thermodynamic of the gas lift process, the hydraulic calculation of the process, in which the extracted production, the amount of gas required, the injection pressures and the location of the valves, should be performed. These parameters were determined to correspond to the oil injection screw compressors manufactured in Romania by INCDT-COMOTI. The essential characteristics of those screw compressors that could be used considering the specificity of the location where the compressor will be mounted will be highlighted also.

1. Scientific and technical description of processes
Continuous artificial eruption or continuous gas lift involves the continuous injection of compressed gases directly into the column of fluid produced by the well in order to reduce their density and, implicitly, the dynamic bottom pressure, allowing the layer to properly flow according to this pressure.

Continuous artificial eruption installations are divided into two categories depending on the type of well completion, namely artificial eruption installations for simple completion and artificial dual-fill eruptions. The gas lift valves are used to discharge the well for its production and continuous gas injection in order to extract a certain fluid flow.

The flow of gases injected into a continuous artificial eruption well to produce a certain fluid flow is influenced by a number of factors such as: physical properties of the produced fluids, impurities, extraction pipes diameter, head pressure, the depth of the injection point and the productivity index of the well [1].
The layer-well working correlation for a continuous artificial eruption well involves determining the behaviour curve of the layer and the behaviour curve of the equipment, as well as establishing coordinates of the layer-well working correlation point, situated at the intersection of the two curves.

Figure 1. The gaslift installation with automated surface equipment (source Parveen Industries - https://parveen.in/includes/show_product.php?id=252).

In the case of continuous artificial eruption, unlike the natural eruption, the behaviour curve of the equipment is determined considering both the gas flow rate injected and the gas injection pressure [1].

The maximum flow rate produced by a continuous artificial eruption well depends on a number of factors such as:

- The pressure in the eruption head that can be considered constant or variable;
- The productivity index of the well, which over a short period of time can be considered constant, but which varies over time as a result of processes occurring in the reservoir;
- The capacity of the gas source (limited or unlimited);
- Injection line pressure (limited value);
- The diameter of the extraction pipes.

Of all these factors, the most important is the capacity of the gas source. If the gas source is very big, so as to be considered unlimited, the determination of the maximum flow produced by a continuous artificial eruption well requires the determination of the behaviour curve of a continuous artificial eruption well.

The screw compressor is part of the volumetric compressors category because the pressure increase is achieved by lowering the workspace volume. The major advantage of these types of compressors is that the compression process is continuous, the machine has no valves and is less sensitive to gas quality [2, 3, 4]. The screw compressors have been growing massively in popularity among users and this happens due to the high level of efficiency, the small gauge dimensions and because there are highly reliable [5]. Oil injection screw compressors are capable of reaching high performances by
realizing major compression reports in one single stage, and, by upgrading the splitting technology/using a better oil, the areas of applicability are continuously expanding [6].

The performance of the screw compressors is determined by the mass flow through it. From a thermodynamic point of view, the screw compressor is considered to be an open system because, during the operation, during the working process, a mass change with the external environment is made [1]. The oil injected into the compressor besides the mechanical effects also has a significant thermodynamic effect by cooling the compressed gas [6]. The compression forces required for all the loads being analysed are significantly lower for an oil-injected screw compressor than for the dry compressor [5].

Generally, from the technical point of view, in case of the screw compressors, the oil injection is done in aspiration, this operation goes to the wear minimization and the seal maximization of parts. The injected oil cools the compressed fluid partially, the physical phenomenon which leads to modifying the thermodynamic process, usually considered adiabatic.

The functional optimization of the screw compressor is driven in the direction of decreasing power necessary to compressing using the injected oil flow [6]. This process significantly modifies thermodynamic parameters of the compression. The oil flow rate for cooling the compressor is the variable parameter used for the optimization of the process.

2. Case study
The following data is known at a continuous artificial eruption well:

- Well depth: \( H = 2800 \text{ m} \)
- Inner diameter of the tubing: \( d_l = 63.5 \text{ mm} \)
- Inner diameter of the column: \( D_i = 127 \text{ mm} \)
- Surface average temperature: \( t_s = 10^\circ \text{C} \)
- Crude Oil density: \( \rho_t = 830 \text{ kg/m}^3 \)
- Reservoir water density: \( \rho_w = 1100 \text{ kg/m}^3 \)
- Gas relative density: \( \rho_{rg} = 0.75 \)
- Surface tension of crude oil: \( \sigma_t = 30 \cdot 10^{-3} \text{ N/m} \)
- Surface tension of water: \( \sigma_w = 60 \cdot 10^{-3} \text{ N/m} \)
- Crude oil viscosity: \( \mu_t = 2.2 \cdot 10^{-3} \text{ Pa} \cdot \text{s} \)
- Gas viscosity: \( \mu_g = 0.022 \cdot 10^{-3} \text{ Pa} \cdot \text{s} \)
- Water viscosity: \( \mu_w = 1 \cdot 10^{-3} \text{ Pa} \cdot \text{s} \)
- The pressure in the eruption head: \( p_2 = 4 \text{ bar} \)

Also, following the calibration of the well, the following data have result:

- Impurities: \( i = 30\% \)
- Bottom hole pressure: \( p_d = 60 \text{ bar} \)
- Static pressure: \( p_c = 90 \text{ bar} \)
- Liquid flow rate: \( Q_l = 50 \text{ m}^3/\text{day} \)
- Well gas flow rate: \( Q_g = 2500 \text{ Nm}^3/\text{day} \)
- Injected gas flow rate: \( Q_{inj} = 30000; 40000; 50000; 60000; 70000; 80000; 90000 \text{ Nm}^3/\text{day} \).

2.1. Thermodynamic analysis of the gas lift process
The gases used in the gas lift process are associated gases that are collected from the separator, which usually have low pressure. In order to be used, they must be compressed and inserted into the well column. Hence the gases are introduced through 7 valves, automatically into the tubing. They expand, mix with the oil and manage to raise it to the surface.

From the thermodynamic point of view, we identify the following processes:

A. Associated gas compression-process requiring an energy consumption with calculated parameters.
B. The introduction of gas from the column into the tubing is accomplished by means of valves. The corresponding thermodynamic process is an adiabatic expansion process. The compressed gas energy must be sufficient to be inserted into the tube.

2.2. Compression calculations

The compressor used as a model is an oil-injected volumetric screw compressor (CU128GM). The oil injection, besides the technological role, influences the thermodynamic compression process in that the oil cools the compressed gases. For this reason, it will be considered a polytrophic process whose exponent will be determined from the experimental data of the compressor [2, 7].

A functional dynamic model was designed so that the screw compressor process may be analysed. The main flows taken into consideration, according to those represented in Figure 2, are:

- Mass flows \( m_a \), \( m_o \), \( m_{a+o} \) for air and oil;
- Power flows for air and oil \( E_a \), \( E_o \), \( E_{a+o} \);
- Necessary power for compressor \( P_c \) and the lost power due to the irreversibility of thermodynamic processes;
- Lost heat flow by the machine to the environment \( Q_p \) and the correspondent entropy flow \( S_{Q_p} \);
- The entropy flows that go through the machine for air and oil \( S_a \), \( S_o \) and \( S_{a+o} \).

![Figure 2. Functional dynamic model for a screw compressor.](image)

For the model presented in figure 2 were used the following equations [1, 2, 8]:

- mass conservation law;
- energy conservation law;
- entropy balance for open systems;
- Gouy–Stodola’s theorem for lost power determination.

Based on the relations from above, a screw compressor with oil injection was created. For the accuracy of the obtained values, the numerical result obtained from the created model were calibrated, for specific regimes, with experimental data so that at the work regime, the outer and inner parameters must be identically.

Parameters to which the compression process is to be dimensioned result from the design of the gas lift process. The results of the calculation, made with a specialized software, are:

- **MAXIMUM LOAD** [100%]
- **The polytrophic exponent** = 1.04207
- **Gas flow rate** [m\(^3\)/day] = 50000  
  **Gas flow rate** [kg/s] = 0.4918
- **Input parameters:**
\[ p_1 \text{[bar]} = 5.00; \quad V_1 \text{[m}^3]\] = 0.12414775; \quad T_1 \text{[°C]} = 20.0 \\
- Output parameters:
\[ p_2 \text{[bar]} = 38.00; \quad V_2 \text{[m}^3]\] = 0.01772902; \quad T_2 \text{[°C]} = 45.0 \\
- Technical mechanics of compression [J/kg] = 131192.682 \\
- Compression power needed [kW] = 50326.038 \\
- Cooling heat \( Q_r \) [kW] = 47681.930

From the analysis of the results one can conclude that due to the technology specific to the oil-injected screw compressor, the polytrophic compression process is approaching to the isothermal process in that the value of the polytrophic exponent is close to 1. This makes the compression power required minimum [9, 10].

The variable parameter that was taken into consideration for the process optimization was the oil flow of compressor cooling.

For the screw compressor with oil injection the temperature decreases according to the oil injected flow rate, fact that can be explained by the part of heat of compressed gas that the oil takes [11]. The thermodynamic process evolves from an adiabatic process to an isothermal one, fact that determines the significantly reduction of compression mechanical work [12].

Based on the obtained data can be observed that due to the oil cooling the value of the adiabatic exponent is reduced to values close to 1 so confirm that the real compression process is similar to an isothermal process fact that determines the maintaining of a low temperature regime of compressor during the functioning and also a reduced power necessary to machine entrainment.

Because the cooling air is stronger than oil heating so that per assembly it will result a decrease in entropy generation speed which means the increase of economy process.

Because the power depends on the mass flow, the oil having big density, concur at the increasing of masic specific air & oil flow results that the more oil is injected the more compressed necessary power increases.

2.3. Valves process calculation

The compressed gas is introduced into the well column and from there it automatically enters the tubing according to the gas lift process. When passing from the column to the tubing the gases suffer an adiabatic expansion. With each valve, depending on the depth and set pressure, the gas enters the column into the tubing.

This requires a consumption of the mechanical work made by the gas that expand from the column pressure to the tubing pressure. The graphical results are shown in figure 3. The results of the thermodynamic expansion calculation for each valve are shown in Table 1.

| Valve no. | \( p_{col} \) [bar] | \( p_{tub} \) [bar] | Specific expansion mechanical work [kJ/kg] | Generated power from gas expansion through the valve [kW] |
|-----------|----------------------|---------------------|------------------------------------------|---------------------------------------------------|
| 1         | 34.5                 | 8.5                 | 30919.92                                  | 15206.42                                          |
| 2         | 33                   | 11.2                | 23695.42                                  | 11653.41                                          |
| 3         | 31                   | 14                  | 17330.49                                  | 8523.13                                           |
| 4         | 29                   | 16.3                | 12504.78                                  | 6149.85                                           |
| 5         | 27                   | 18                  | 8770.16                                   | 4313.16                                           |
| 6         | 25                   | 19                  | 5920.32                                   | 2911.61                                           |
| 7         | 22.7                 | 19.8                | 2940.41                                   | 1446.09                                           |

If we add up the gas consumed powers when passing through the valves (50203.67 kW) the value is comparable to the one required to compress the gas (50326.038 kW), which shows that the system is balanced and that the power used for compression is consumed to introduce the gas into the pipe.
Considering the station parameters and the types of screw compressors manufactured in Romania by INCDT-COMOTI [13], before choosing the optimal solution, two types of compressors can be selected:

- Screw compressor with oil injection CHP220;
- Screw compressor with oil injection CU128GM.

Both the CHP 220 compressor and the CU128GM compressor show the following possible applications:

- Replacement of old GKN 10 piston compressors used in PETROM-OMV gas lift stations;
- High pressure compressors for national transport or distribution pipelines;
- Various applications required by users in the country or abroad, which require increasing the pressure and flow of the gas used.

Both compressor can be used in:

- Oil/gas extraction stations;
- Offshore stations due to their relatively small size, relatively low weight and low operating noise;
- Petrochemical industry or industrial applications;
- Pumping of gas into pipelines or storage tanks;
- Gas supply system for gas turbines (booster);
- Marine platforms exploitation.

![Figure 3. Gas injection mechanism through valves.](image)

From the comparative analysis of the operating parameters of the compressor types specified above, it is advisable to choose as the compression unit for the gaslift process of the CU128 GM compressor. Operating parameters of the CU128GM high pressure discharge screw compressor (see figure 4) are as follows:

- Maximum Discharge pressure: 45 bar
- Suction pressure: 4.5 bar
- Volumetric ratio: 4.8
- By modulating the output pressure different volumetrically ratio can be obtained: 2.6; 3.5; 4.8 and the suction pressure can go to maximum 9 bar.
- Theoretical flow rate:
Minimum driving rotor speed 1148 - Theoretical flow rate 230 m³/hour
Maximum driving rotor speed 4591 - Theoretical flow rate 921 m³/hour

- Multiplier ratios:
  
  Electrical engine drive 1500 RPM - multiplier ratios 1.2; 1.2407; 1.2830 ......2.5588
  
  Electrical engine drive 3000 RPM - multiplier ratios 1.2; 1.2407; 1.2830 ......1.5208

Transmission ratios are obtained by correlating the number of toothed gear teeth on the motor shaft driven by the electric motor and the driving rotor shaft, and by varying the transmission ratio, the requested flow in the range is ultimately obtained.

Experimental samples for the CU128GM compressor were performed on the COMOTI stand (see figure 4), and after processing the generated data (see figure 5), the performance graph of the compressor (see figure 6) was obtained.

![Figure 4. CU 128 GM V₁ = 4.8 compressor ready for tests.](image)

![Figure 5. Print screen with the screw compressor test data.](image)

![Figure 6. CU 128 GM V₁ = 4.8 compressor for the stand is tested: a) aspiration and discharge pressure; b) power variation.](image)

3. Conclusion

To operate a well in gaslift, a quantity of gas is required (typically associated gases collected from the separator), which is compressed at the process pressure.

Gas compression is the only energy consumption (which translates into costs) for the gaslift process. For this reason, the dimensioning of the compression process must be rigorously made.
The paper presents the gas thermo-dynamic calculations made taking into account several gas compression variants for determining the optimum design solution and the maximum compression efficiency of the gas using an oil injection screw compressor. In this paper a compression process for an oil compressor has been dimensioned which allows a polytrophic process to be performed with a polytrophic exponent close to unit, which reduces the specific mechanical work of compression. The dimensioning of the compression process has been made correctly because the compressing power of the gas is equal to the power required to pass it through the well valves.

Due to the high flexibility and maintainability, oil-injected screw compressors can be used both in oil/gas extraction stations, offshore stations due to relatively small dimensions, relatively low weight and low operating noise, petrochemical industry or applications industrial piping, gas pumping in pipelines or storage tanks, the gas booster system, marine platforms. Another advantage of the oil-injected screw compressor is the low discharge temperature of compressed gas.

Several types of compressors have been studied for such a process and analysed for the operating parameters, the choice as compression unit of the CU128 GM compressor is advisable. It is underlined that this type of compressor will ensure the operation of the compressor station at optimal parameters.

Also, one of the reasons why this type of screw compressor can be considered is also the changes that may occur in the evolution of gas-lift conditions, for which the CU128GM compressor would operate at normal conditions and in these conditions unlike by the CHP220 compressor that would function with much diminished volumetric or adiabatic efficiency.

The minimal energy consumptions for compressors is achieved by optimizing the compression process fact that means a significant reduction in the operating costs.

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