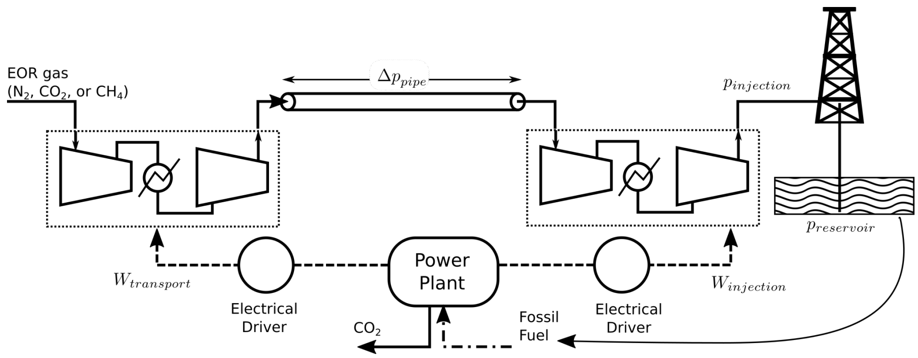

Figure 1: The flow diagram for the transport and injection of gas into an oil reservoir.

1 Compression power requirement in gas EOR projects

The energy requirement for the compression of the gas phase for the transport of the gas to the reservoir location from the source, e.g., a power plant that supplies CO_2, and the injection of the transported gas into the reservoir is the main contributor to the high energy demand of a gas EOR project. The energy requirement for the transport depends on the flow rate of the gas stream, the length, diameter, and roughness of the pipeline, and the physical properties of the gas phase. The compression energy for the injection of the gas is a function of the gas type and the reservoir pressure. In the following sections, we describe a simple procedure for the design of the compressor stations and pipelines for the transport and injection of a known flow rate of an EOR gas. We later use the procedure to quantify the energy requirement for a gas EOR project.

2 Gas transmission pipelines

Figure 1 shows the flow diagram for the transport and injection of gas into an oil reservoir. The gas stream, which is assumed to be at atmospheric pressure and environmental temperature, is compressed in a multi-stage compressor station with inter-coolers (a heat exchanger that decreases the temperature of the compressed gas stream before entering a new compression stage). The gas is delivered at the well head at a pressure of 80 bar and the environmental temperature. The gas is injected into the oil reservoir by means of another multi-stage compressor station. The compressors are driven by electrical drivers with electrical energy that comes from a fossil fuel power plant. This assumption facilitates the calculation of the CO_2 emission of the gas EOR process.

Here, we first design a gas transport pipeline for a known flow rate of a specified gas at known operating conditions. Then, we calculate the pressure drop in the gas pipeline, which we use later in the calculation of the compression power for the transmission of the gas stream. At the end, we study the effect of the pipe diameter on the power requirement of the compressor for transporting the same amount of gas.

2.1 Pressure drop

Different equations are suggested for the calculations of pressure drop as a function of pipeline and flow specifications, which must be specified in the prescribed unit for the specific equation. Here, we use the Panhandle equation that reads

$$Q_h = 0.028E\left[\frac{p_1^2 - p_2^2}{S^{0.961}ZTL_m}\right]^{0.51} d^{2.53}$$

$$\frac{Q_h}{0.028Ed^{2.53}} = \left[\frac{p_1^2 - p_2^2}{S^{0.961}ZTL_m}\right]^{0.51}$$

the upstream pressure (p_1[psia]) is calculated by:

$$p_1 = \left(S^{0.961}ZTL_m\left(\frac{Q_g}{0.028Ed^{2.53}}\right)^{1/0.51} + p_2^2\right)^{0.5}$$

where E is efficiency factor (average value of 0.9), Q_g [MMscfD] is the gas flow rate, p_2 [psia] is pressure at the outlet end of the pipeline, L_m [mile] is the pipe length, T [^{o}R] is temperature, S [-] is the specific gravity of the gas (at 21^{o}C and 1 atm), Z is the compressibility factor, and d [inch] is the internal pipe diameter which is discussed in the next section.

2.2 pipe diameter

The average diameter of a gas transmission pipeline is calculated by

$$d = \left(\frac{4Q}{\pi v_g}\right)^{0.5}, \tag{1}$$

where d [m] is the inside diameter of the pipe, Q [m^3/s] is the volumetric gas flow rate, and v_g [m/s] is the average velocity of the gas in the pipeline. We prefer to choose larger velocities to make the pipeline diameter as small as possible and minimize the costs of the pipe material. However, choosing a large gas velocity increases the noise and corrosion in the pipeline. Additionally, a high gas velocity corresponds to a higher friction and a larger pressure drop in the pipeline, which increases the power consumption in the compressors. Here, we design the pipeline for the highest permitted velocity, shown in Table 1, and then study the effect of choosing larger pipe diameters on the compression power requirements.

Table 1: Maximum gas velocity for the transport pipeline design

Gas	Velocity [ft/s]	Velocity [m/s]
CO_2	50	15.2
N_2	80	24.4
CH_4	80	24.4

2.3 Compressor stages

The number of stages that is required to compress a gas stream from pressure p_{in} to pressure p_{out} is calculated by

$$n_{stage} = \frac{\ln(p_{in}/p_{out})}{\ln r_{comp}},$$

where $r_{comp} = p_{out}/p_{in}$ is the compression ratio for each compressor. The number of compressors must be an integer number. Therefore, we choose the floor of n_{stage} as the number of compressors. We choose a compression ratio of 3.5 here.

2.4 Compression power (exergy) requirement

The minimum compression power is required for an isentropic compressor, i.e., a reversible adiabatic compression process. Using this assumption and with known gas type (or composition x_i), input temperature T_{in} [K], input pressure p_{in} [K], and compression ration r_{comp}, we first quantify the minimum energy requirement of a compressor in the following steps:

1. Calculate the output pressure: $p_{out} = r_{comp} p_{in}$
2. Calculate the entropy $S_{in}(p_{in}, T_{in}, x_i)$ and enthalpy $H_{in}(p_{in}, T_{in}, x_i)$ of the input gas stream using the physical property package CoolProp.
3. Calculate the output temperature T_{out} [K] by solving the following non-linear equation: $S_{in}(p_{in}, T_{in}, x_i) - S_{out}(p_{out}, T_{out}, x_i) = 0$.
4. Calculate the enthalpy of the output -compressed- gas stream $H_{out}(p_{out}, T_{out}, x_i)$
5. Calculate the isentropic compression (theoretical) work: $W_{th} = H_{out} - H_{in}$.

The theoretical compression work can be converted to a practical value by considering the efficiency factor of the compressor, its electrical driver, and the efficiency factor for electricity production, η_{comp}, η_{driver}, and η_{pp} respectively, i.e.,

$$W_{pr} = \frac{W_{th}}{\eta_{comp}\eta_{driver}\eta_{pp}}.$$

Typical values for these efficiency factors are shown in Table 2.

Table 2: Typical values for the efficiency factors of compressors, electrical drivers, and power plants

Device	Compressor	Electrical driver	Power plant
Efficiency factor (%)	70	90	40

2.5 Other exergy requirements

Besides the power requirement in the compressors, the drilling operation and production and installation of the pipes require a considerable amount of exergy. Here, we only calculate the exergy requirement for the production of steel pipes. To that end, we first need to calculate the weight of the gas transport pipeline, which depends on the pipe thickness that can be calculated by

$$t_{pipe} = \frac{p_{design} OD_{pipe}}{2 F S_y E},$$

where t_{pipe} [inch] is the thickness of the pipe, p_{design} [psi] is the design pressure, OD_{pipe} [inch] is the outside diameter of the pipe, S_y [psi] is the yield strength of the pipe material (60000 psi for X60 steel pipe), F [-] is and efficiency factor with an average value of 0.72, and E [-] is the weld joint factor with an average value between 0.6 to 1.0 (here we choose 0.8). The weight of the pipe is calculated by

$$m_{pipe} = \frac{\pi}{4} \left((d_{pipe} + t_{pipe})^2 - d_{pipe}^2 \right) L_{pipe} \rho_{steel},$$

where ρ_{steel} [kg/m^3] is the density of steel. The exergy requirement for the production of steel and production of a pipe is reported by Szargut to be ex_{pipe} =60×10^6 J/kg. We assume that the pipeline will be in operation for a life span of t_{life} = 30 years. Then we can calculate the exergy flow of the pipeline $\dot{E}x_{pipe}$ [J/s] by

$$\dot{E}x_{pipe} = \frac{m_{pipe} ex_{pipe}}{t_{life}}.$$