NETL Life Cycle Inventory Data
Process Documentation File

Process Name:	Compressor, Single-Stage Centrifugal, Operation
Reference Flow:	1 kg of compressed fluid
Brief Description:	This unit process calculates the power required to compress a given fluid and the fugitive emissions associated with operation.

Section I: Meta Data

Geographical Coverage: N/A **Region:** N/A

Year Data Best Represents: N/A

Process Type: Basic Process (BP)

Process Scope: Gate-to-Gate Process (GG)

Allocation Applied: No

Completeness: All Relevant Flows Captured

Flows Aggregated in Data Set:

☑ Process ☑ Energy Use ☐ Energy P&D ☐ Material P&D

Relevant Output Flows Included in Data Set:

Releases to Air:	☐ Greenhouse Gases	☐ Criteria Air	☐ Other
Releases to Water:	☐ Inorganic	☐ Organic Emissions	☐ Other
Water Usage:	☐ Water Consumption	☐ Water Demand (throughput)	
Releases to Soil:	☐ Inorganic Releases	☐ Organic Releases	☐ Other

Adjustable Process Parameters:

m_dot_tonne	*[tonne/day] Fluid mass flow rate*
mol_wt	*[kg/mol] Molecular weight of fluid*
P_in_MPa	*[MPa] Fluid pressure at compressor inlet*
T_in	*[K] Fluid temperature at compressor inlet*

cp_in	*[J/g-K] Fluid isobaric specific heat capacity at compressor inlet*
cv_in	*[J/g-K] Fluid isochoric (constant volume) specific heat capacity at compressor inlet*
rho_in	*[kg/m^3] Fluid density at compressor inlet*
P_critical	*[MPa] Fluid critical pressure*
P_out_MPa	*[MPa] Fluid pressure at compressor outlet*
rho_out	*[kg/m^3] Fluid density at compressor outlet*
cp_out	*[kJ/kg-K] Fluid isobaric specific heat capacity at compressor outlet*
z_vendor	*[dimensionless] Fluid compressibility factor provided by vendor*
eff_poly_v	*[dimensionless] Average fluid compressibility factor (if vendor compressibility factor is not provided)*
eff_isen_v	*[dimensionless] Compressor isentropic efficiency (vendor provided)*
eff_motor	*[dimensionless] Efficiency of the electric motor to drive the compressor*
NG_emm_factor	*[kg/MW-yr] Natural gas emission factor for compression stations*
T_H2O_cool_out	*[K] Maximum outlet temperature of aftercooler water*

Tracked Input Flows:

Power [Electric Power]	*[Technosphere] Electricity required for compressor*
Carbon dioxide [intermediate product]	*[Technosphere] Fluid input (flow name will need to be changed for different fluids)*

Tracked Output Flows:

Carbon dioxide [intermediate product]	*Reference flow (flow name will need to be changed for different fluids)*
Carbon dioxide [Inorganic emissions to air]	*Emission to air (flow name will need to be changed for different fluids)*

Section II: Process Description

Associated Documentation

This unit process is composed of this document and the data sheet (DS) *Stage3-O-Gas_Fluid_Compressor.xls*, which provides additional details regarding relevant calculations, data quality, and references.

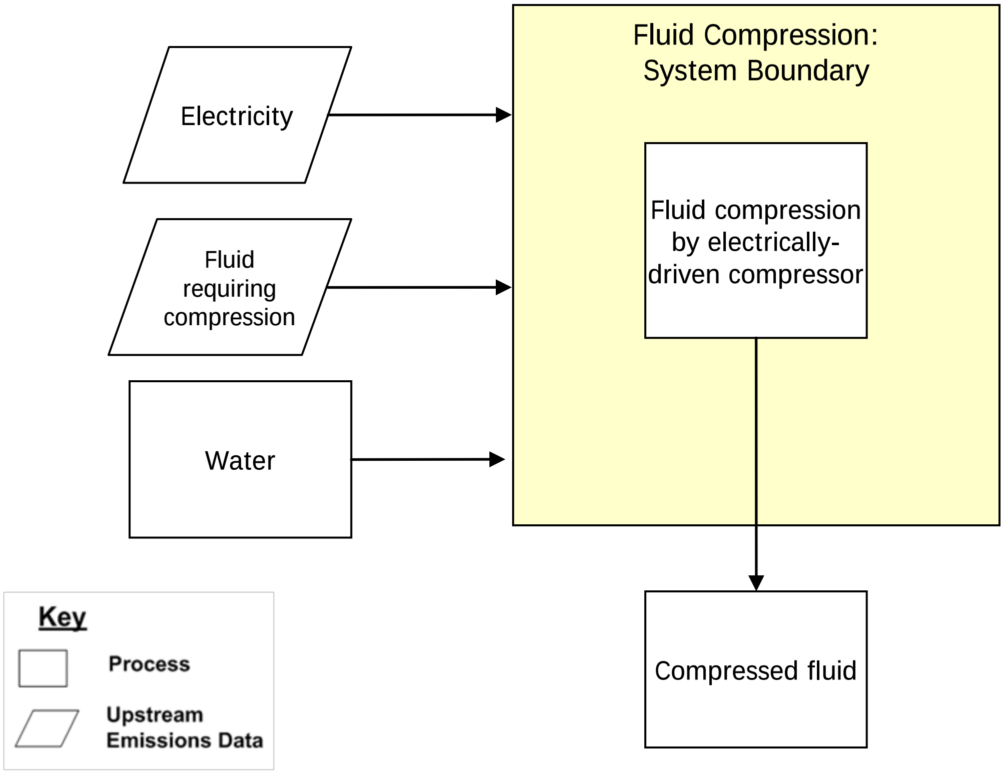
Goal and Scope

This unit process provides a summary of relevant input and output flows associated with the operation of a single-stage, centrifugal compressor with any fluid at any combination of inlet and outlet temperature/pressure. This unit process also provides fugitive emissions of the fluid being compressed and water usage for an aftercooler. Select thermodynamic and physical properties of the fluid must be known for the inlet and outlet states. The reference flow of this unit process is: 1 kg of compressed fluid.

Boundary and Description

Figure 1 provides an overview of the boundary of this unit process. Rectangular boxes represent relevant sub-processes, while trapezoidal boxes indicate upstream data that are outside of the boundary of this unit process. As shown, the upstream emissions from electricity are calculated in another unit process. The methods for calculating these operating activities are described below.

Figure 1: Unit Process Scope and Boundary



The power required for a compressor depends on multiple design variables that are defined by upstream and downstream operating conditions and working fluid properties. The operating conditions that inform the analysis are the fluid pressures and temperatures at the inlet and outlet of the compressor, the number of compressor stages, and the volumetric flow rate at the compressor inlet. Fluid properties that are required for the analysis are the inlet specific heats, inlet and outlet densities, and fluid molecular weight. These values can be found in various reference books and websites. For the default values in the unit process, fluid properties for carbon dioxide were obtained from the National Institute of Standards and Technology (Lemmon et al., n. d.)

The compressor inlet pressure, P_i, and temperature, T_i, are set by the outlet conditions of the process immediately upstream from the compressor, if known. In most cases, the outlet pressure, P_x, must be assumed. The mass flow rate, , represents the amount of fluid volume that is sent downstream by the compressor. The inlet volumetric flow rate, Q_i, represents the amount of fluid volume that passes through the compressor inlet in a set amount of time that is determined by dividing mass flow rate by the inlet fluid density, ρ (**Equation 1**).

Equation 1 - Volumetric Flow Rate

$$Q_i = \frac{\dot{m}}{\rho}$$

The ratio of specific heats, γ, also known as the adiabatic index or heat capacity ratio, is a dimensionless value that is determined through **Equation 2**, where c_p is the specific heat of the working fluid at constant pressure and c_v is the specific heat at constant volume. The specific heat at constant pressure, c_p, represents the amount of heat transfer that is required to raise one unit mass of the working fluid 1 degree at a specific temperature and constant pressure. The specific heat at constant volume, c_v, is defined in the same manner, with the exception that volume is held constant instead of pressure (Avallone et al., 1996).

Equation 2 - Ratio of Specific Heats (Adiabatic Index)

$$\gamma = \frac{c_p}{c_v}$$

Another fluid property that must be calculated is the average compressibility factor (Z_a). The compressibility factor is a measure of how much a given gas behavior deviates from that predicted by the ideal gas equation, **Equation 3**, which relates fluid pressure (P) and volume (V) to temperature (T) and fluid quantity (n in moles) via the universal gas constant (R). The compressibility factor (Z) is the ratio of the actual molar volume at a given pressure to that predicted by the ideal gas law, **Equation 4** (Brucat, n.d.). Both inlet and outlet compressibility factors are needed to provide an average compressibility factor via **Equation 5**. Alternatively, vendors may provide the compressibility factor for a given compressor/fluid (Avallone, et al., 1996).

Equation 3 - Ideal Gas Equation

Equation 4 - Compressibility Factor

Equation 5 - Average Compressibility Factor

$$Z_a = \frac{Z_i + Z_x}{2 * Z_i}$$

To determine the fluid state at the outlet, the pressure and temperature must be known. If temperature is unknown, a compressor outlet temperature can be predicted using **Equation 6**, which relates the outlet temperature to inlet temperature (T_i) and pressure (P_i), outlet pressure (P_x), ratio of specific heats (γ), and polytropic efficiency (η_p, discussed below) (Cumpsty, 2003).

Equation 6 - Predicted Compressor Outlet Temperature

$$T_x = T_i * \left(\frac{P_x}{P_i}\right)^{\frac{\gamma-1}{\eta_p * \gamma}}$$

It is also necessary to assume the number of compression stages, *n*, that the compressor will utilize. Multiple stages are used in a compressor to overcome limitations caused by temperature rise, polytropic head, and mechanical stresses in a single compressor stage. A typical commercial compressor uses between two and eight stages.

The polytropic efficiency represents the percentage of total work that is reversible at constant pressure and volume. The polytropic efficiency, η_p, of a compressor can be defined via **Equation 7** as logarithmically related to the volumetric flow rate (Q_i) in cubic feet per minute (cfm) (Cumpsty, 2003). Because the equation is specific to cfm, the unit process includes a conversion factor from m^3/s to cfm. Vendors may provide a polytropic efficiency for a given compressor.

Equation 7 - Polytropic Efficiency (Q_i in cfm)

$$\eta_p = 0.014 * \ln(Q_i) + 0.6$$

The isentropic efficiency is the ratio of the work input to an isentropic process (in this case isentropic compression) to the work input to the actual process between the same inlet and exit pressures. This can be calculated through **Equation 8**, using the previously calculated polytropic efficiency, or may be provided by the vendor (Avallone, et al., 1996).

Equation 8 - Isentropic Efficiency

$$\eta_C = \frac{\left(\frac{P_x}{P_i}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(\frac{P_x}{P_i}\right)^{\frac{\gamma-1}{\gamma * \eta_p}} - 1}$$

Using the defined values, the power requirements of a compressor can be determined thermodynamically using **Equation 9** if the fluid starts out below critical pressure (Avallone, et al., 1996). The equation assumes that the compressor will operate adiabatically with additional power required to offset isentropic, polytropic, and compressibility losses. When the starting pressure is above the critical pressure,

Equation 9 overestimates the power required, so **Equation 10** is used to calculate pumping power required to raise the pressure of a sub-cooled or super-critical fluid (McCollum et al., 2006). For simplicity pump efficiency is assumed to be the same as compressor polytropic efficiency (η_p).

Equation 9 - Compressor Power

$$W = \frac{\dfrac{\dfrac{\gamma}{\gamma - 1} * P_i * Q_i * \left(\left(\dfrac{P_x}{P_i} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right) * Z_a}{\eta_c}}{\eta_p}$$

Equation 10 - Pump Power

The compressor is assumed to be driven by an electric motor. Electric motors in industrial applications usually exhibit efficiencies of about 95 percent (DOE, 1996). The predicted electricity usage is thus scaled by the assumed motor efficiency.

This unit process also provides an estimate of fugitive emissions from the compressor using emission rates from compressor stations on natural gas pipelines (Holloway et al., 2006). The natural gas emission rates (EF_{NG} on a mass basis assuming 0.7 kg/m^3 density for methane) are scaled by both the average fluid pressure across the compressor (P_{avg}) and the molecular weight (m_w) of the fluid according to **Equation 11**, similar to the method presented in the IPCC report for carbon dioxide. The equation in the IPCC report used only the molecular weights, but given that this unit process can allow much higher pressures than that normally experienced in natural gas pipelines, the difference pressures should be accounted for. The equation assumes that the pressure in the natural gas pipelines was at the critical pressure for methane (4.5992 MPa). The emission factor is then related to the reference flow by multiplying the fluid emission factor by the compressor power per kg of fluid compressed. The tracked fluid input is then increased to account for the fugitive emissions.

Equation 11 - Compressor Emission Factor

Water usage by an aftercooler is also included as an option in the unit process. To define the amount of water used, the carbon dioxide and water outlet temperatures must be known or assumed, and for simplicity inlet water is assumed to be 288.7 K (60°F) and just slightly pressurized giving it a fixed isobaric specific heat of 4,183 kJ/kg-K. Additionally, the energy balance requires the CO_2 outlet isobaric specific heat to be specified. The source of water is assumed to be a wet cooling tower, and the fraction of raw water withdrawal, recycling, and discharge are based on the same fractions as used in previous NETL studies (NETL, 2010).

Depending on the process, it may not be reasonable to assume single-stage compression. In this case, a multi-stage compressor can be assembled by linking the output of this unit process to another instance of itself. Care must be taken to ensure that the outlet and inlet fluid properties match. Another consequence of this approach is that aftercoolers can be specified for individual stages. To split a desired pressure increase (inlet pressure P_i and outlet pressure P_x) across the number of stages (n), Equation 12 should be used to find the pressure ratio (PR), which is multiplied to the input pressure of each stage to find the outlet pressure (McCollum, et al., 2006). For example, for an overall pressure increase from 0.1 MPa to 15 MPa in a 5-stage compressor, the first stage inlet pressure will be 0.1 MPa and the outlet pressure will be 0.2724 MPa (0.1 MPa · PR = 0.1 · 2.724). The second stage would be 0.7421 MPa (0.2724 MPa · 2.724) and so on.

Equation 12 - Multi-stage Pressure Ratio

$$\frac{\quad}{\quad}^{-}$$

Table 1: Unit Process Input and Output Flows

Flow Name	Value	Units (Per Reference Flow)
Inputs		
Power [Electric Power]	1.99E-05	**MWh**
Carbon dioxide [intermediate product]	**1.00E+00**	**kg**
Water (ground water) [Water]	5.55E-01	kg
Water (surface water) [Water]	5.55E-01	kg
Outputs		
Carbon dioxide [intermediate product]	**1.00**	**kg**
Carbon dioxide [Inorganic emissions to air]	1.19E-05	kg
Water (wastewater) [Water]	0.29	kg

* **Bold face** clarifies that the value shown *does not* include upstream environmental flows.

Embedded Unit Processes

None.

References

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Section III: Document Control Information

Date Created: September 18, 2012

Point of Contact: Timothy Skone (NETL), Timothy.Skone@NETL.DOE.GOV

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Section IV: Disclaimer