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EXERGONOMICS OF AN EOR (OCDOPUS) PROJECT

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Abstract – The combined production of power, carbon dioxide, process steam, hot water, and compressed nitrogen for EOR is considered. Exergy-flow diagrams are used to evaluate plant efficiency. The exergy efficiency of the plant is defined as the sum of the exergy outputs divided by the exergy of the consumed fuel. Estimations of the invested exergy, net exergy coefficient and the sum of the specific exergy consumption are presented.

INTRODUCTION

In a preceding paper,[1] a zero-emission power plant (OCDOPUS project) was analyzed for use at an oil field. The plant produces CO_2 for EOR, along with compressed N_2. No waste gases are released from this plant. Here, we evaluate the effectiveness of this plant by means of exergy calculations. The exergy efficiency η_{ex} is the exergy output E_{out} divided by the exergy input E_{in}. Using exergonomics, we may minimize the exergy consumption[2] (Eq. 1). This minimization does not replace economic calculations but it is an important first step in system optimization. Because of the lack of economic data, we use exergies both for current flows and also for investments in equipment. The important relation becomes

$$Z = 1/\eta_{ex} + 1/K_{ex}, \tag{1}$$

where the net exergy coefficient is $K_{ex} = \dot{E}_{del}\tau_n / E_{inv}$, $\dot{E}_{del}$ = exergy flow delivered, τ_n = life time, E_{inv} = exergy invested. The criterion Z has the following minimum with respect to the exergy efficiency η_{ex}: $Z_{min} = [1+ (-dK_{ex}/d\eta_{ex}{}^{1/2}]/K_{ex}$ with $\eta_{ex}^{opt} = K_{ex}/(-dK_{ex}/d\eta_{ex})^{1/2}$. If η_{ex} exceeds its optimal value η_{ex}^{opt}, there is wasteful energy use.[3] Numerical values are used for the exergies and efficiencies of industrial processes.[4] As in economics, we discount exergy by assuming that the time τ_n is less than the life time τ, and we use $\tau_n/\tau = 0.25$.

EOR AS A FUNCTION OF FUEL CONSUMPTION

We will now estimate the extraction factor and the relation of additional oil recovery to injected CO_2. In his comprehensive review, Bondor[5] stated that "one barrel of incremental oil can be recovered by use of 5 mcf of purchased carbon dioxide", which seems doubtful. Some experimental results have been published.[6] Early tests in 1967-77 demonstrated that the additional oil (28.8 mt) was six times greater than the injected CO_2 (4.8 mt). Data on the increased oil-extraction factor and a much less optimistic ratio between oil and CO_2 (0.32-0.89) for subsequent tests at many oil fields are given in Table 1. As stated in Ref. 1, the mass-ratio oil/CO_2 = 0.5 is marginal for commercial use. For a smaller ratio, the consumed fuel exceeds the incremental oil. If crude oil is used as fuel at a rate equal to the increased production, the net benefit is produced power.

Table 1. Experimental data on extraction increases.

Parameter, unit	Mass ratio of oil produced to CO_2				
	Sergejev	Olchov	Radaev	Kozlov	Abdrakhmanov
Permeability, $(\mu m)^2$	0.23	0.04	1.54	0.24-0.28	0.548
Viscosity, mPa-s	5.7	0.72	30.7	7.0-6.1	4.0
Temperature, ˚C	40	27	26.5	30-31	36
Pressure, MPa	18.1	18.5	12.7	12.6	16.8
Number of productive wells	50	76	86	50	325
Injections	16	25	27	22	93
Initial extraction, %	22.8	28.8	42.7	42.6	45.2
Water flooding, %	51.0	28.3	82.7	80.9	80.2
CO_2 in porous volume, %	15	15	12	12	30
CO_2/H_2O ratio	1:1.5	1:1	1:3.1	1:2.8	1:3
Extraction increase, %	10.4	12.4	12.8	10.4	13.0
Oil extraction per mt CO_2	0.56	0.48	0.89	0.67	0.32

OCDOPUS FLOWS

The exergy flows for a 10 MW power plant are shown in Fig. 1. The plant produces nitrogen or power, as an example 7 kg/s of compressed nitrogen (300 bar) or 10 MW of power. Liquid CO_2, process steam and hot water are normal plant effluents. The use of oxygen for underground combustion appears to be prohibited in some countries. The OCDOPUS plant can also provide a supply of oxygen.

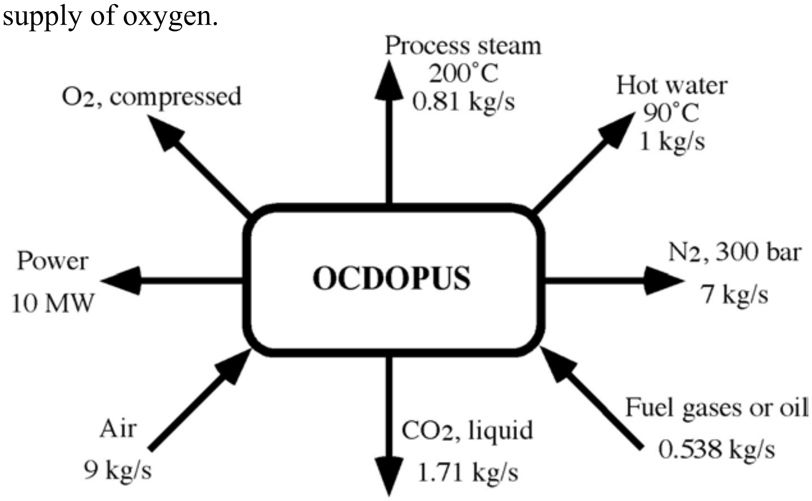

Fig. 1. Production and consumption in the OCDOPUS plant.

EXERGY DIAGRAMS

The usual Sankey-Grassman diagrams for exergy flows are given in Fig. 2. Incoming fuel and air (zero exergy) is converted to compressed N_2 or electrical power, N_2 is assumed to be an ideal gas. The exergies of minor flows of hot water have been neglected.

For CO_2, the data of Ref. 4 are used to calculate the exergy by adding the exergy of CO_2 in dry air at 1 bar to the exergy of compression to 60 bar at 293 K. The two modes of operation, N_2

and power production in Fig. 2, relate to the following efficiencies: $\eta_{ex}^{N_2}$ = (3.47+1.48+0.75)29 ≈ 0.20, η_{ex}^{power} = (10+1.48+0.75)29 ≈ 0.42.

The main problem in net exergy calculations is the estimation of the masses of non-existent, i.e. not yet constructed, components. Statistical data by Zaritski[7] (Fig. 3) give the specific mass of heavy-duty gas turbines as a function of specific power. The greater the specific power, the less the specific mass is. In the OCDOPUS project, the mass-flow rate is 53.8 kg/s and the specific power 10,000/53.8≈185 kJ/kg. From Fig. 3, we obtain a maximum specific power of about 10 kg/kW, i.e. 100 mt at 10 MW. Data for O_2 plants give an average value of 50 mt/kg/s of O_2, i.e. 100 mt for our plant with 2 kg/s. Thus, the total mass of the OCDOPUS plant is about 200 mt or 20 kg/kW. The exergy use for mainly stainless steel is about 100 MJ/kg.[4] The exergy remaining in the steel amounts to about 6.9 MJ/kg.[8] The total exergy use in construction is then about 20 TJ.

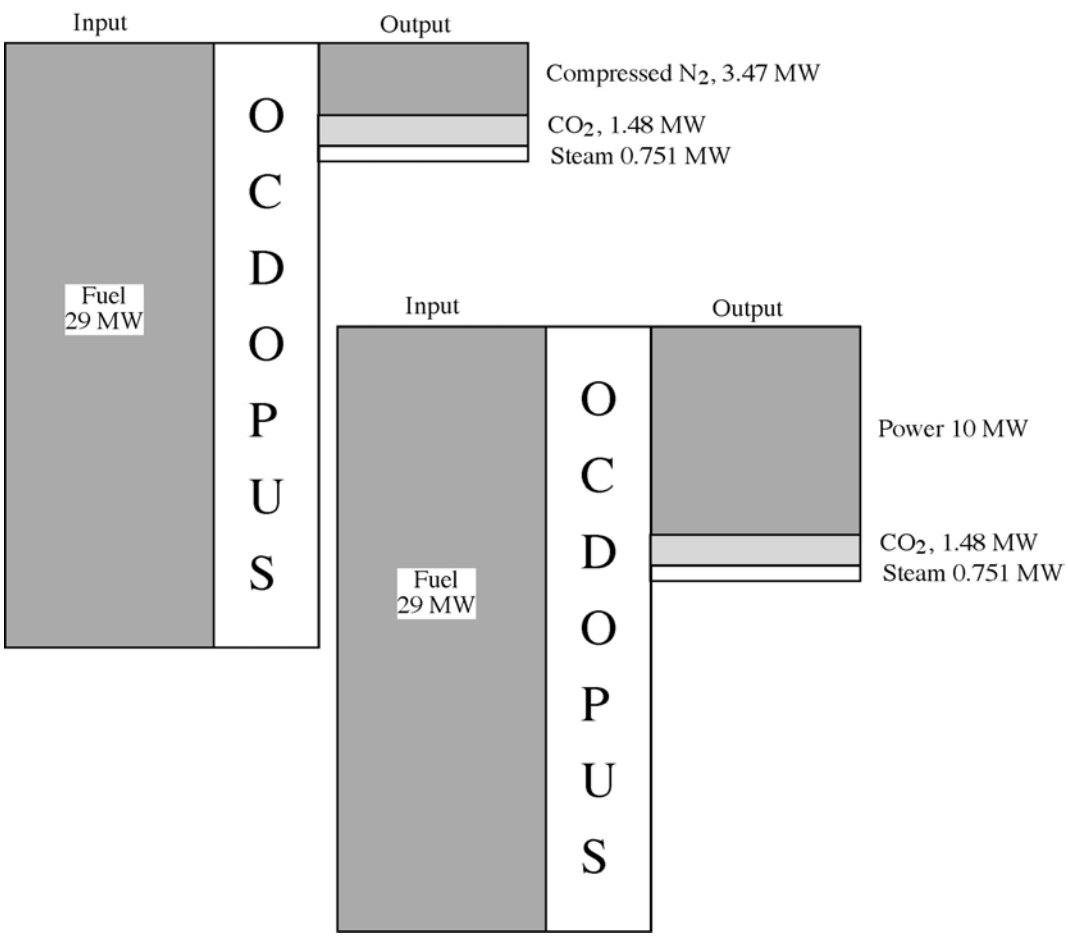

Fig. 2. Exergy flows of the OCDOPUS plant in the nitrogen and power modes.

The delivered exergy in a time τ_n of 8 yr with 20 Ms of working time/yr equals $10^7 \times 8 \times 2 \times 10^7$ = 1600 TJ. The net exergy coefficient K_{ex} is equal to 1600/20=80, which is a very high value and implies a small contribution to the Z criterion as in many fuel-fired power plants. If this result is verified by more rigorous calculations, then OCDOPUS optimization will only require the maximization of the exergy efficiency η_{ex}.

CONCLUSIONS

The exergy efficiency of OCDOPUS is high, 42% in the power mode and 20% in the compressed N_2 mode. Past experiments show only marginal oil enhancement with increased fuel consumption. The exergy used in the construction phase has a minor role in the exergonomic criterion (Eq. 1). Therefore, the optimized target may only be the exergy of the operating efficiency.

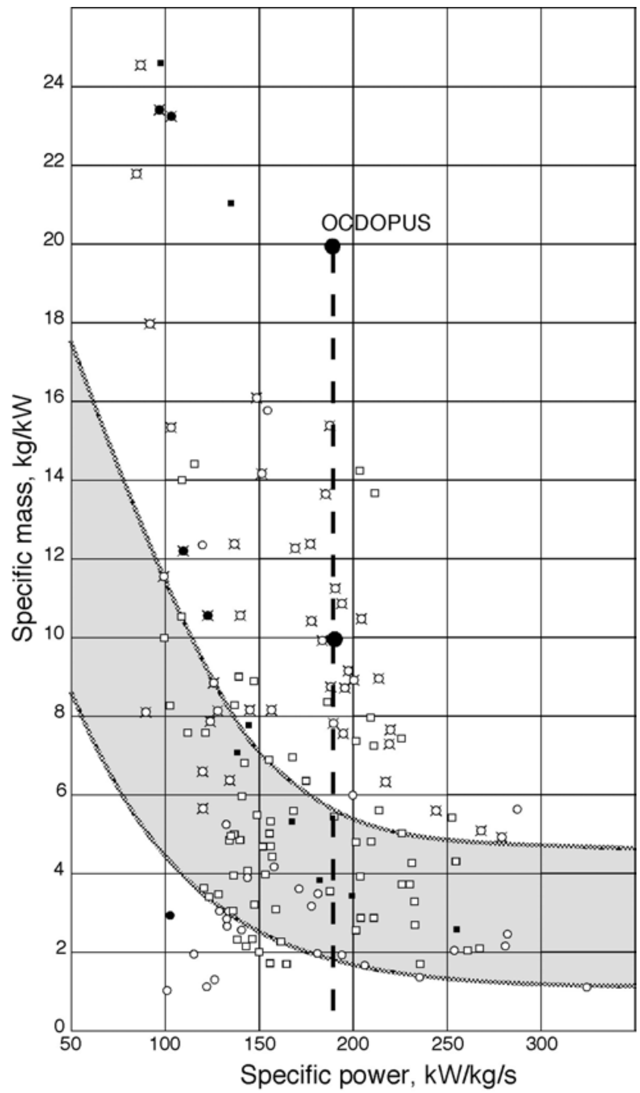

Fig. 3. Statistical data of the specific masses of heavy-duty gas turbines vs the specific power[7] and location of the OCDOPUS point.

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