Technical solution abilities of flue gas thermal power consumption on compressor station Stružec

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Natural gas is frequently used in motors that drive the compressors. Burning gases in motors are producing flue gases with very high temperature. That temperature depends on motor power and gas composition, and ranges from approximately 400 °C to 650 °C.

Specific heat of flue gases in compression station Stružec is appreciable. The proof is that specific heat is sufficient to heat the gathering station (GS), measuring station MS-1 and CS Stružec. Specific heat of flue gases in compression stations Žutica or Lipovljani is even higher.

In continuation of this article the calculations of heating power of flue gases at CS Stružec and spherical flow of gas that contains energy value, which is equivalent to thermal power of flue gases, will be performed.

Key words: enthalpy of mixtures, specific heat, heat exchangers, circulating water

1. INTRODUCTION

Large quantities of different energies are used in oil and gas production industry. During production and preparation of oil, gas and water for transport, electrical energy is used to drive electrical engines of downhole, process, submersible, dosing, injection, firefighting and dispatching pumps and compressor units.

Gas is used as fuel in boiler rooms, hot water systems, and frequently in motors that drive the compressors. Many years ago on our oil and gas fields such fuel gas for internal consumption amounted to about 25% of total produced gas quantities in Croatia.

It is undisputable that large quantities of all kinds of energy are used in production of oil and gas and it is therefore necessary to strive continuously to find new technical and technological solutions which will allow their production at lowest consumption of "external" energy.

2. FLUE GAS

In recent winters we experienced a gas crisis that affected most of Europe. It is clear that all kinds of energy will have to be used economically in the future. Technological solutions are therefore required to make oil and gas production cheaper. Primarily are needed such technical solutions that enable lower consumption of external thermal and electrical energy.

Utilization of thermal energy contained in flue gases can be the first step in such direction. Compressors are mostly driven by gas engines, and flue gases are released during gas combustion. Temperature of flue gases ranges from 400 °C to 650 °C, and even higher. From so high temperatures it is quite clear that flue gas has a very high heating power.

2.1. CS Stružec main data

Three compressors are in continuous operation at CS Stružec. They are driven by 400 kW gas engines. Each engine burns 2 333 m^3/gas per day, at 1 800 revolutions per min.

Compressor capacity is from 20 000 to 80 000 m^3/day, inlet pressure 1 to 2 bar, pressure after gas compression is 51 bar, and gas lift pressure is 31 bar.

Compressed gas temperature ranges from 27 °C and 35 °C, and flue gases temperature is 555.1 °C.

Distance between CS Stružec and MS-1 is 100 m, and distance from CS Stružec to GS Stružec is the same.

Currently 63 wells are in production on Stružec oil field. Table 1. includes production parameters of Stružec oil field.

Table 1. Stružec oil field production parameters

	Oil	Brine	Oil/brine mixture	Share of brine	Gas
	(m^3/day)	(m^3/day)	(m^3/day)	(%)	(m^3/day)
MS-1	125	260	385	67.53	42 000
MS-3	130	640	770	83.12	49 000
MS-4	70	290	360	80.56	38 000
Total	325	1 190	1 515	78.55	129 000

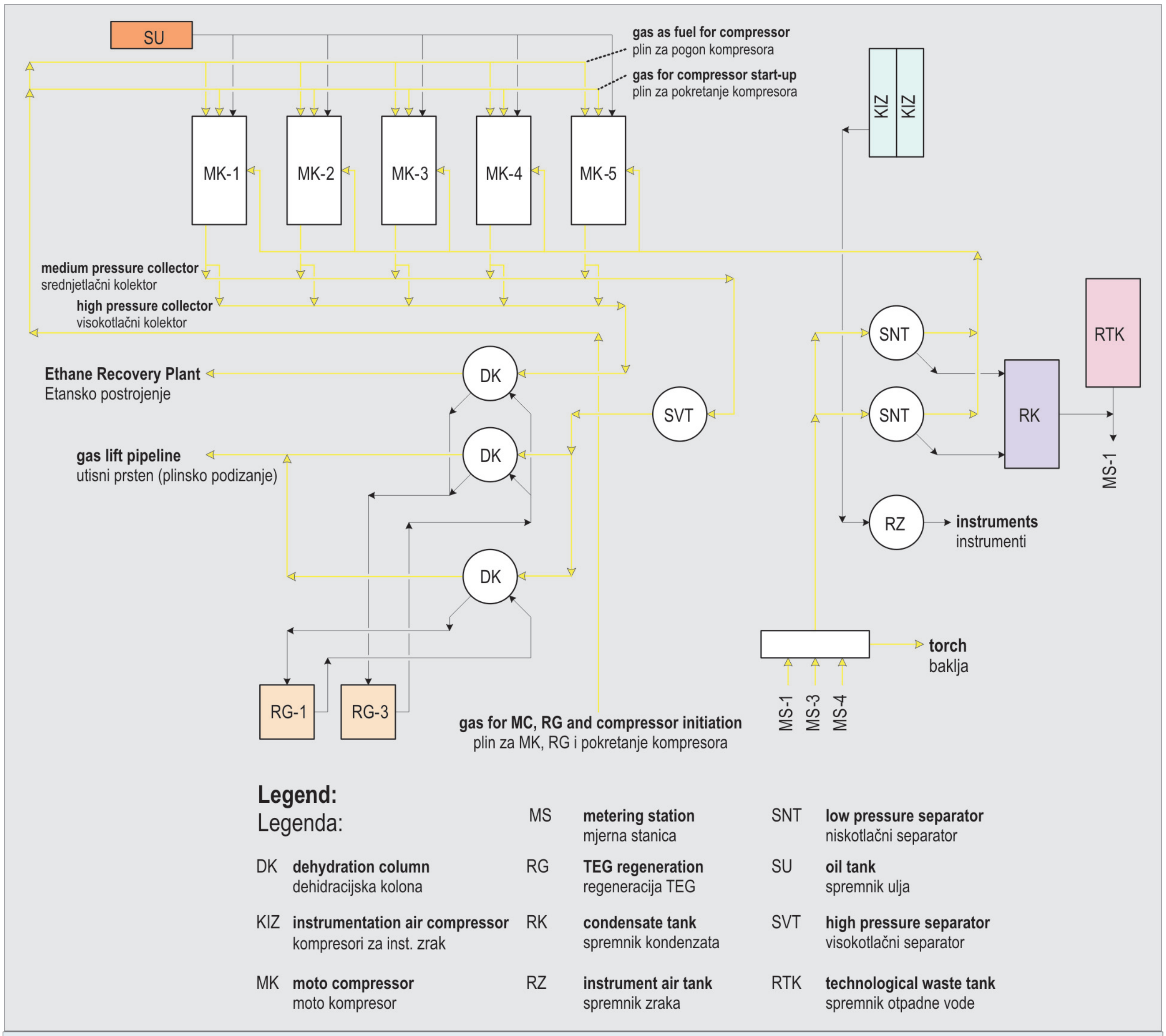

Fig. 1. Technological scheme of CS Stružec
Sl. 1. Tehnološka shema KS Stružec

Figure 1 presents technological diagram of CS Stružec.

2.2. Burning of fuel

All the necessary heat in households, transportation, electricity generation and industry comes from fuel and nuclear facilities. Technically, the most important sources of heat are solid, liquid and gaseous fuels, which accumulate heat in the form of chemical energy.

Combustion of fuel is a process in which oxidation of combustible components of fuel takes place. In that manner the energy of chemical bonds is converted into thermal energy with or without flame. Chemical energy stored in fuel is converted into thermal energy through oxidation reaction. Such energy can be further transformed into other forms of energy, such as mechanical and electrical.

In the combustion process fuel and oxygen, which is used from air, are reactants. Flue gases and residue are combustion products. Combustible components are: carbon, hydrogen and sulphur (organic, sulphidic and pyritic). After combustion, the residue includes nitrogen, oxygen, ash and moisture.

The air contains: 20.947% oxygen (O_2), 78.084% nitrogen (N_2), 0.934% argon (Ar) and 0.033% carbon dioxide (CO_2).

In traces are found: neon (Ne), helium (He), krypton (Kr), sulphur dioxide (SO_2), methane (CH_4), hydrogen (H_2), nitrogen oxide (N_2O), xenon (Xe), ozone (O_3), nitrogen dioxide (NO_2), iodium (I_2), ammonium (NH_3), carbon monoxide (CO). Mass ratio for oxygen in the air is 0.232 and for nitrogen 0.768.

Combustion of fuel can be complete and incomplete. Complete combustion occurs after complete oxidation of combustible components from fuel: carbon, hydrogen and sulphur into CO_2, H_2O and SO_2. In incomplete combustion products of combustion still contain combustible components: carbon, carbon monoxide and methane, as well as other hydrocarbons. In such cases, for example, carbon monoxide (CO) contained in flue gas can oxidize into carbon dioxide (CO_2). Such form of combustion occurs due to insufficient quantity of oxygen, or when the quantity of oxygen is insufficient in all parts of the reactive space.

When combustion is incomplete, chemical energy still remains in unburnt fuel and unburnt components, flue gases, which represents energy losses.

Total combustion of 1 kg of methane, according to the Law on conservation of mass, requires 4 kg of oxygen.

Mol mass values:

- methane (CH_4) M = 16 kg/kmol
- oxygen (O_2) M = 32 kg/kmol
- water (H_2O) M = 18 kg/kmol
- carbon dioxide (CO_2) M = 44 kg/kmol

$$CH_4+2 \cdot O_2 \rightarrow CO_2+2 \cdot H_2O$$

$$1\ \text{kmol}\ CH_4+2\ \text{kmol}\ O_2 \rightarrow 1\ \text{kmol}\ CO_2 + 2\ \text{kmol}\ H_2O$$

$$16\ \text{kg}\ CH_4 + 2 \cdot 32\ \text{kg}\ O_2 \rightarrow 44\ \text{kg}\ CO_2 + 2 \cdot 18\ \text{kg}\ H_2O\ /\ :16$$

$$\frac{16 \text{kg} CH_4}{16} + \frac{2 \cdot 32 \text{kg} O_2}{16} \rightarrow \frac{44 \text{kg} CO_2}{16} + \frac{2 \cdot 18 \text{kg} H_2O}{16}$$

$$1\ \text{kg}\ H_4+4\ \text{kg}\ O_2 \rightarrow 2.75\ \text{kg}\ CO_2 + 2.25\ \text{kg}\ H_2O$$

Gas fuel can be in the form of one component or be a mixture of several hydrocarbon components. The combustion of gaseous fuels is an egzothermal oxidation process of combustible components.

Minimal quantity of oxygen (kmol O_2/kmol of fuel) for given gas composition:

$$O_{min} = 0.5 \cdot (CO + H_2) + 2 \cdot CH_4 + 3 \cdot C_2H_6 + \sum \left(n + \frac{m}{n}\right) \cdot C_nH_m - O_2 \quad \text{[kmol/kmol]} \tag{1}$$

Minimal required quantity of air for combustion expressed in kmol of air per 1 kmol of fuel:

$$V_{Z\,min} = \frac{O_{min}}{0.21} \text{ [kmol/kmol]} \tag{2}$$

Combustion processes usually require higher quantity of air than minimal, so that actual quantity of air amounts to:

$$V_{Zstv} = \lambda \cdot V_{Z\,min} \text{ [kmol/kmol]} \tag{3}$$

When $\lambda < 1$, combustion is incomplete, and when $\lambda > 1$, air excess amounts to $(\lambda - 1) \cdot V_{zmin}$.

Air excess factor for gas combustion is λ=1.05-1.25.

In complete combustion of gaseous fuels flue gases include the same components as flue gases in complete combustion of solid and liquid fuels.

Natural gas used as fuel frequently contains combustible and non-combustible components. Combustible components are: methane (CH_4), ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), etc., and non-combustible components are mostly: nitrogen (N_2) and carbon dioxide (CO_2).

During the combustion, combustible components of fuel combine with oxygen from the air. Incomplete combustion can occur after inlet of air excess, if the temperature required for combustion and turbulence are not high enough.

Oxygen must get to all combustible particles in sufficient quantity for their complete combustion. In practice, it is not easily achieved or ensured under all fuel combustion conditions.

Complete combustion of combustible matter is achieved after supply of excess air.

Combustion equation for methane (CH_4):

$$CH_4 + 2 \cdot H_2O \rightarrow CO_2 + \frac{4}{2} H_2O \tag{4}$$

Combustion equation for all other hydrocarbons can be derived from equation (4):

$$CH_m + \left(n + \frac{m}{4}\right) \cdot O_2 \rightarrow n \cdot CO_2 + \frac{m}{2} H_2O \tag{5}$$

Table 2. shows combustion equations for combustion of certain hydrocarbons, theoretical quantities of air required for combustion of 1 m³ of gas, and quantities of flue gas generated by burning of 1 m³ of gas.

After petroleum gas processing at Ethane Recovery Plant in Ivanić Grad, the gas (predominantly methane) is transported to CS Stružec, where it is used as fuel for driving of gas engines, and for other requirements.

Table 2. Equations for gas combustion and combustion products

Combustion equations	Theoretically required gas (m³/m³)			Volume of produced flue gas (m³/m³)			
	O_2	N_2	O_2N_2	CO_2	H_2O	N_2	$CO_2+H_2O+N_2$
$CH_4+2\ O_2 \rightarrow CO_2+H_2O$	2	7.52	9.52	1	2	7.52	10.52
$C_2H_6+3.5\ O_2 \rightarrow 2\ CO_2+3\ H_2O$	3.5	13.16	16.66	2	3	13.16	18.16
$C_3H_8+5\ O_2 \rightarrow 3\ CO_2+4\ H_2O$	5	18.80	23.80	3	4	18.80	25.80
$C_4H_{10}+6.5\ O_2 \rightarrow 4\ CO_2+6\ H_2O$	6.5	24.44	30.94	4	5	24.44	33.44
$C_5H_{12}+8\ O_2 \rightarrow 5\ CO_2+6\ H_2O$	8	30.08	38.08	5	6	30.08	41.08

Table 3. Gas composition

Gas composition	Gas as fuel	Gas for dispatching to Ethane Recovery Plant
	(vol. share)	(vol. share)
N_2	1.14	0.01
CO_2	0.00	1.38
C_1	97.31	82.63
C_2	1.54	6.73
C_3	0.01	5.01
i-C_4	-	1.00
n-C_4	-	2.08
i-C_5	-	0.46
n-C_5	-	0.43
C_{6+}	-	0.27
Mol mass (kg/kmol)	16.399	20.764
Density (kg/m^3)	0.695	0.881 4
Relative density (air=1)	0.567	0.683 2
Gross calorific value (MJ/m^3)	37 779	46 025
Net calorific value (MJ/m^3)	34 047	41 724
Compressibility factor	0.998	0.993 8

Theoretical volume of oxygen (VO_2), required for combustion of natural gas in gas engines at CS Stružec is calculated using the following equations:

methane (CH_4): $CH_4 + 2 \cdot O_2 \rightarrow CO_2 + 2 \cdot H_2O$ (6)

methane (C_2H_6): $C_2H_6 + 3.5 \cdot O_2 \rightarrow 2 \cdot CO_2 + 3 \cdot H_2O$ (7)

propane (C_3H_8): $C_3H_8 + 6 \cdot O_2 \rightarrow 3 \cdot CO_2 + 4 \cdot H_2O$ (8)

Theoretically required quantity of gas:

$$V_{O2} = \frac{2CH_4 + 3.5C_2H_6 + 5C_3H_8 - O_2}{100} \quad (9)$$

V_{O2}=2 006 m^3 oxygen/m^3 gas

where:
VO_2 theoretically required quantity of oxygen m^3 oxygen/m^3 gas
O_2 oxygen contained in natural gas %

Theoretically required quantity of air for combustion of 1 m^3 of gas:

$$V_{tz} = 4.76\ O_2 \quad (10)$$

V_{tz}=9.552 3 m^3 air/m^3 gas

where:
V_{tz} theoretically required quantity of air for combustion of 1 m^3 of gas m^3 air/m^3 gas

Practically required volume of air for combustion of 1m^3 of gas:

$$V_{pz} = \lambda \cdot 4.76 \cdot VO_2$$

V_{pz}=11.935 7 m^3 air/m^3 gas

where:
λ air excess factor 1.1 do 1.25

Quantity of wet flue gas generated during combustion of 1 m^3 of gas:

$$V_{dpl} = \frac{N_2 + CO_2 + H_2 + 3 \cdot CH_4 + 5 \cdot C_2H_6 + 7 \cdot C_3H_8}{100} + (V_{pz} - V_{O2}) \quad (11)$$

V_{dpl}=12.938 m^3/m^3 ≈ 13 m^3/m^3

where:
V_{dpl} quantity of wet flue gas m^3 of flue gas/m^3 gas
N_2, CO_2, H_2 components of natural gas

Composition of wet flue gas can be determined applying the following equations:

- share of carbon dioxide (CO_2') in flue gas

$$CO_2' = \frac{CO_2 + CH_4 + 2 \cdot C_2H_6 + 3 \cdot C_3H_8}{V_{dpl}} \cdot 100\ [\%] \quad (12)$$

CO_2'=1.004 2 ⇒ 7.70%

- share of water (H_2O') in flue gas

$$H_2O' = \frac{H_2 + 2 \cdot CH_4 + 3 \cdot C_2H_6 + 4 \cdot C_3H_8}{V_{dpl}} \cdot 100\ [\%] \quad (13)$$

H_2O'=1.992 8 → 16.00%

- share of nitrogen (N_2') in flue gas

$$N_2' = \frac{N_2 + 4.76 \cdot \lambda \cdot V_{O2}}{V_{dpl}} \cdot 100\ [\%] \quad (14)$$

N_2'=91.900 8 → 72.50%

- share of oxygen (O_2') in flue gas

$$O_2' = \frac{V_{O2} \cdot (\lambda - 1)}{V_{dpl}} \cdot 100\ [\%] \quad (15)$$

O_2'=3.857 7 ⇒ 3.80%

Natural molecular mass of flue gas:

$$m = r_1 \cdot m_1 + r_2 m_2 + r_3 m_3 + r_4 m_4 \quad (16)$$

m=27.784

where:
m molecular mass of flue gas mixture (m_1=28; m_2=44; m_3=18; m_4=32)
r_1 to r_4 share of flue gas components %

1 kmol of flue gas has thermal power of Q_t.

Table 4. Flue gas composition

Flue gas composition	Volume share [%]
Water, water vapour (H_2O)	16.00
Carbon dioxide (CO_2)	7.70
Nitrogen (N_2)	72.50
Oxygen (O_2)	3.80
Σ	100.00

3. SPECIFIC HEATS OF GASES

If 1 kg of gas is heated, in the first case at constant volume (V = const.) and in the second case at constant temperature (T = const.), then:

$$q = c \cdot \Delta T \quad (17)$$

According to the first law of thermodynamics:

$$dg = du + A \cdot p \cdot dv = c \cdot dt \quad (18)$$

During heating at V = const., $dv = 0$, and therefore:

$$c_v = \left(\frac{\partial q}{\partial T}\right)_v = \left(\frac{\partial u}{\partial T}\right)_v \quad (19)$$

During heating at p = const.:

$$c_p = \left(\frac{\partial q}{\partial T}\right)_p = \left(\frac{\partial u}{\partial T}\right)_p + A \cdot p\left(\frac{\partial v}{\partial T}\right)_p \quad (20)$$

then:

$$c_p = c_V + A \cdot R \quad (21)$$

or:

$$c_p - c_V = A \cdot R \quad (22)$$

where:

A thermal equivalent of mechanical operation kJ/kgfm

c_p specific heat at constant pressure kJ/kg K

c_v specific heat at constant volume kJ/kg K

3.1. Internal energy of ideal gases

$$du = cu \cdot dT = \left(\frac{\partial u}{\partial T}\right) \cdot dT ; \left(\frac{\partial u}{\partial T}\right) = c_u \quad (23)$$

$$u = c_v \cdot dT + u_0$$

If c_v = const., then:

$$u = c_v \cdot (T - T_0) + u_0 \text{ [kJ/kg]} \quad (24)$$

$$U = G \cdot u \text{ [kJ]} \quad (25)$$

Integration constant uo is the inner energy of ideal gas at To and it remains undefined. Differences in inner energies are generally taken into consideration. The integration constant u_o is therefore taken as value u_o = 0. But actually uo only at T_o = 0 K = -273.16 °C disappears and only then equals zero.

3.2. Mean specific heat of gas

In calculations with higher temperature differences, dependence of specific heat on temperature must be taken into account.

Calculation of specific heats by means of internal energy u is a relatively complex calculation for practical use. It is calculated by means of mean specific heat T_o and T [°C].

$$q = \int_{To}^{T} c \cdot dt = [c]_{To}^{T} \cdot (T - T_o) \text{ [°C]} \quad (26)$$

$$q = \frac{1}{T - T_o}\int_{To}^{T} c \cdot dt \text{ [kJ/kg K]} \quad (27)$$

For 1 mole of gas:

$$m \cdot u_2 - m \cdot u_1 = [c_v]_{To}^{T} \cdot (T - T_o) \quad (28)$$

For 1 kg of gas:

$$u_2 - u_1 = \frac{[c_v]_{To}^{T}}{m} \cdot (T - T_o) \quad (29)$$

Specific heat of a mixture of gases:

$$c_p = \sum(g_i \cdot c_{pi}); \; c_v = \sum(g_i \cdot c_{vi}) \quad (30)$$

or

$$c_p = \sum(r_i \cdot c_{vi}); \; c_v = \sum(r_i \cdot c_{pi}) \quad (31)$$

If T considerably differs from 0°, mean specific heat is calculated from specific heat capacity cp according to the equation:

$$[c_p]_{T1}^{T2} = \frac{[c_p]_{T0}^{T2} \cdot T_2 - [c_p]_{T0}^{T1} \cdot T_1}{T_2 - T_1} \text{ [kJ/kg °C]} \quad (32)$$

4. ENTHALPY

Enthalpy is the total energy of specific gas, which includes inner energy (u) and potential energy or thermodynamic potential ($p \cdot v$).

The quantity ($p \cdot v$) which had to be supplied to gas. The quantity of heat supplied to 1 kg of gas at constant pressure for its heating from temperature T_1 to T_2 (K):

$$q = u_2 - u_1 + p \cdot (v_2 - v_1) \quad (33)$$

After rearranging of equation (33) it follows:

$$q = (u_2 + p \cdot v_2) - (u_1 + p \cdot v_1) \quad (34)$$

Expressions in brackets are total energy content of gas in a certain state. That quantity is called enthalpy and is termed as:

$$i = u + p \cdot v \quad (35)$$

After insertion of equation (35) into equation (34) we obtain:

$$q = i_2 - i_1 \quad (36)$$

Quantity of heat of supplied 1 kg of gas at constant pressure for its heating from temperature T_1 to T_2.

Since:

$$q = i_2 - i_1$$

It means that:

$$i_2 - i_1 = c_p \cdot (T_2 - T_1) \quad (37)$$

If the initial state of 273.16 K (0 °C) is selected, when enthalpy is i = 0, then:

$$i - i_0 = c_p \cdot (T - T_0) \quad (38)$$

$$i - 0 = c_p \cdot T \text{ [J/kg]} \quad (39)$$

Enthalpy as the content of heat can be expressed in other units of gas quantities:

$$i = c_p \cdot T \text{ [J/kmol]} \quad (40)$$

$$i = c_p' \cdot T \text{ [J/m}^3\text{]} \quad (41)$$

$$Q_t = i_2 - i_1 \text{ [kJ/mol]} \quad (42)$$

where:

$$i_3 = c_{p3}\Big|_0^{T3} \cdot T_3 \quad (43)$$

$$i_2 = c_{p2}\Big|_0^{T2} \cdot T_2$$

i_3 enthalpy of flue gas at t_3 = 555,1 °C (828.26 K)
i_2 enthalpy of flue gas at t_2 = 204 °C (477.16 K)

Mean specific heat of flue gas mixture at known composition volume will be:

$$i_3 = c_{p3}\Big|_0^{T_3} \cdot T_3 = r_1 \cdot c_{p3N_2} + r_2 \cdot c_{p3CO_2} + r_3 \cdot c_{p3H_2O} + r_4 \cdot c_{p3O_2} \quad (44)$$

$$i_3 = 555.1 \cdot 32.264\,6 = 17\,910.08 \text{ kJ/kmol}$$

where:

t_3 flue gas temperature 555.1 °C
r_1 share of N_2 in flue gas mixture %
r_2 share of CO_2 in flue gas mixture %
r_3 share of H_2O in flue gas mixture %
r_4 share of O_2 in flue gas mixture %
c_{p3N2} specific heat of N_2 at t_3 = 555.1°C (828.26 K) 30.21 kJ/kmol
c_{p3CO2} specific heat of CO_2 at t_3 = 555.1 °C (828.26 K) 45.223 kJ/kmol
c_{p3H2O} specific heat of H_2O at t_3 = 555.1 °C (828.26 K) 35.504 kJ/kmol
c_{p3O2} specific heat of O_2 at t_3 = 555.1 °C (828.26 K) 31.56 kJ/kmol

$$i_2 = c_{p2}\Big|_0^{T_2} \cdot T_2 = r_1 \cdot c'_{p2N_2} + r_2 \cdot c'_{p2CO_2} + r_3 \cdot c'_{p2H_2O} + r_4 \cdot c'_{p2O_2}$$

$$i_2 = 204 \cdot 31.074\,7 = 6\,339.24 \text{ kJ/kmol}$$

where:

t_2 flue gas temperature 204 °C
c_{p2N2} specific heat of N_2 at t_2 = 204 °C (477.16 K) 30.21 kJ/kmol
c_{p2CO2} specific heat of CO_2 at t_2 = 204 °C (477.16 K) 45.223 kJ/kmol
c_{p2H2O} specific heat of H_2O at t_2 = 204 °C (477.16 K) 35.504 kJ/kmol
c_{p2O2} specific heat of O_2 at t_2 = 204 °C (477.16 K) 31.56 kJ/kmol

Mean specific heat of flue gas at 90 °C (363.17 K):

$$i_1 = c_{p1}\Big|_0^{T_1} \cdot T_1 = r_1 \cdot c'_{p1N_2} + r_2 \cdot c'_{p1CO_2} + r_3 \cdot c'_{p1H_2O} + r_4 \cdot c'_{p1O_2}$$

$$i_1 = 2\,750.46 \text{ kJ/kmol}$$

where:

t_1 flue gas temperature 90 °C
c_{p1N2} specific heat of N_2 at t_1 = 90 °C (363.16 K) 29.141 kJ/kmol
c_{p1CO2} specific heat of CO_2 at t_1 = 90 °C (363.16 K) 37.887 kJ/kmol
c_{p1H2O} specific heat of H_2O at t_1 = 90 °C (363.16 K) 33.717 kJ/kmol
c_{p1O2} specific heat of O_2 at t1 = 90 °C (363.16 K) 29.512 kJ/kmol

By thermal power of flue gas water-saturated trietylenglycol (TEG) can be heated to 204 °C. That heat can be used for heating of water (90 °C - 70 °C). Remaining flue gas heat (temperature between 90 °C and 35 °C) can be used for underfloor heating of different spaces, and for heating of gas and air prior to inlet into gas engines, where it is burnt.

Difference in enthalpies of flue gases within the temperature range of 555.1 °C to 204 °C

$$\Delta i_{3-2} = i_3 - i_2 \quad (45)$$

$$\Delta i_{3-2} = 11570.84 \text{ kJ/kmol}$$

Difference in enthalpies of flue gas within the temperature range of 204 °C to 90 °C

$$\Delta i_{2-1} = i_2 - i_1 \quad (46)$$

$$\Delta i_{2-1} = 3\,588.78 \text{ kJ/kmol}$$

Total quantity of flue gas produced during 1 hour:

$$q_{dpl} = q_{dpl\,1m^3} \cdot q_{pl} \cdot n \quad (47)$$

$$q_{dpl} = 3\,795.09 \text{ m}^3\text{/h}$$

$$q_{dpl} = 1.054\,2 \text{ m}^3\text{/s}$$

where:

q_{dpl} quantity of flue gas produced during 1 hour m³/h
q_{dpl1m3} quantity of flue gas obtained during combustion of 1 m³ of gas 13 m³/h
q_{pl} volume flow of burned gas in gas engine 97.31 m³/h
n number of compressor units 3

Number of flue gas moles at t_3 = 555.1 °C:

$$M_{dpl\,3} = \frac{p_{atm} \cdot q_{dpl}}{8\,314 \cdot T_3} \quad (48)$$

$$M_{dpl\,3} = 0.015\,5 \text{ kmol/s}$$

where:

M_{dpl3} number of flue gas moles at 555.1 °C kmol/s
p_{atm} atmospheric pressure - 101 325 Pa

Heating power of flue gas at 555.1 °C:

$$Q_3 = M_{dpl\,3} \cdot i_3 \quad (49)$$

$$Q_3 = 977\,796 \text{ kJ/h}$$

Number of flue gas moles at t_2 = 204 °C:

$$M_{dpl\,2} = \frac{p_{atm} \cdot q_{dpl}}{8\,314 \cdot T_2}$$

$$M_{dpl\,2} = 0.026\,9 \text{ kmol/s}$$

where:

M_{dpl2} number of flue gas moles at 204 °C kmol/s

Heating power of flue gas at 204 °C:

$Q_2 = M_{dpl\,2} \cdot i_2$

$Q_2 = 613\,908$ kJ/h

Heating power contained in flue gas in the temperature range from 555.1° to 204 °C:

$Q_{3-2} = Q_3 - Q_2$

$Q_{3-2} = 363\,888$ kJ/h

Number of flue gas moles at $T_1 = 90$ °C:

$$M_{dpl\,1} = \frac{p_{atm} \cdot q_{dpl}}{8\,314 \cdot T_1}$$

$M_{dpl\,1} = 0.035\;4$ kmol/s

where:

M_{dpl1} number of flue gas moles at 90 °C kmol/s

Heating power of flue gas at 90 °C:

$Q_1 = M_{dpl\,1} \cdot i_1$

$Q_1 = 350\,532$ kJ/h

Heating power contained in flue gas in the temperature range from 204 °C to 90 °C:

$Q_{2-1} = Q_2 - Q_1$

$Q_{2-1} = 263\,376$ kJ/h

Table 5. shows the heating value of gas used as fuel for driving of gas engines at CS Stružec.

Calculation of gas volume whose thermal power is equivalent to the heat contained in flue gas in the range of temperatures from 555,1 °C to 35 °C.

$Q_3 = 977\;796$ kJ/h

$Q_0 = 230000$ kJ/h (read from diagram in Figure 2.)

$\Delta Q = Q_3 - Q_0$

$\Delta Q = 747\;796$ kJ/h

The quantity of gas (energy value) which corresponds to the equivalent of flue gas heat:

$$q_p = \frac{\Delta Q}{H_i \cdot \eta_1 \cdot \eta_2} \qquad (50)$$

$q_p = 27.95$ m³/h

$q_p = 244\,842$ m³/year.

where:

q_p volume flow of gas used as fuel m³/h

H_i net calorific value of gas 33 025.3 kJ/m³

h_1 energy efficiency ratio of installations 0.9

h2 energy efficiency ratio of hot water boiler 0.9

By utilizing thermal power of flue gas from CS Stružec, 244 842 m³/year of gas can be saved.

There are six compressor stations at INA-Naftaplin which have gas driven engines. In addition to CS Stružec, the following compressor stations with gas engines are also in operation:

- *CS CPS Molve III*
  FAIRBANKS-MORSE / WORTHINGTON DRESSER x 2 (2 500 kW) - about 15 000 m³/day of gas is used;
- *CS Etan*
  DRESSER-RAND KVR 616 x 2 (3 600 kW; only one is in operation, at reduced capacity) - about 12 000 m³/day of gas is used
- *CS Lipovljani*
  WAUKESHA L7042GSI / I-R 4RDS3 x 4 (750 kW) - about 4 000 m³/day of gas is used, and on WAUKESHA

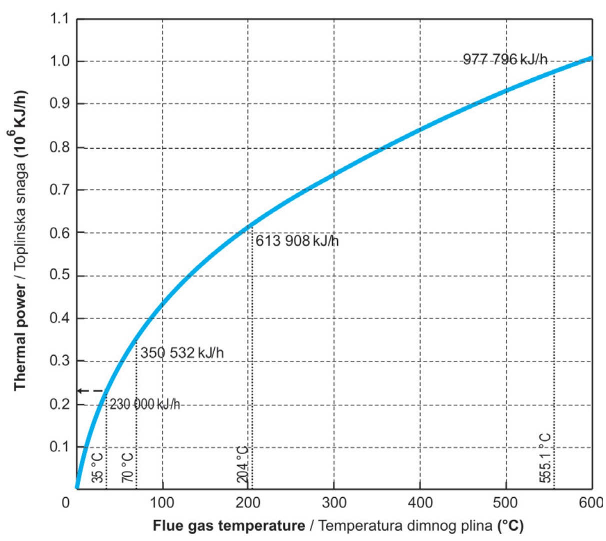

Fig. 2. Interdependance of flue gases thermal power and temperature at CS Stružec
Sl. 2. Međuovisnost toplinske snage dimnih plinova i temperatura na KS Stružec

Table 5. Calorific value of gas used as fuel to drive the gas engines at CS Stružec

Gas composition	Vol. share	H_{ig} Calorific value of gas share	ρ Density of gas share	H_{ig} Heating power of gas	H_i Heating power of gas
	%	kJ/kg	kg/m³	kJ/ m³	kJ/ m³
CH_4	0.973 1	49 949	0.716 8	33 929	33 016.3
C_2H_6	0.015 4	47 436	1.356	64 322	990.6
C_3H_8	0.000 1	46 348	2.019	93 577	9.4
Σ					33 025.3

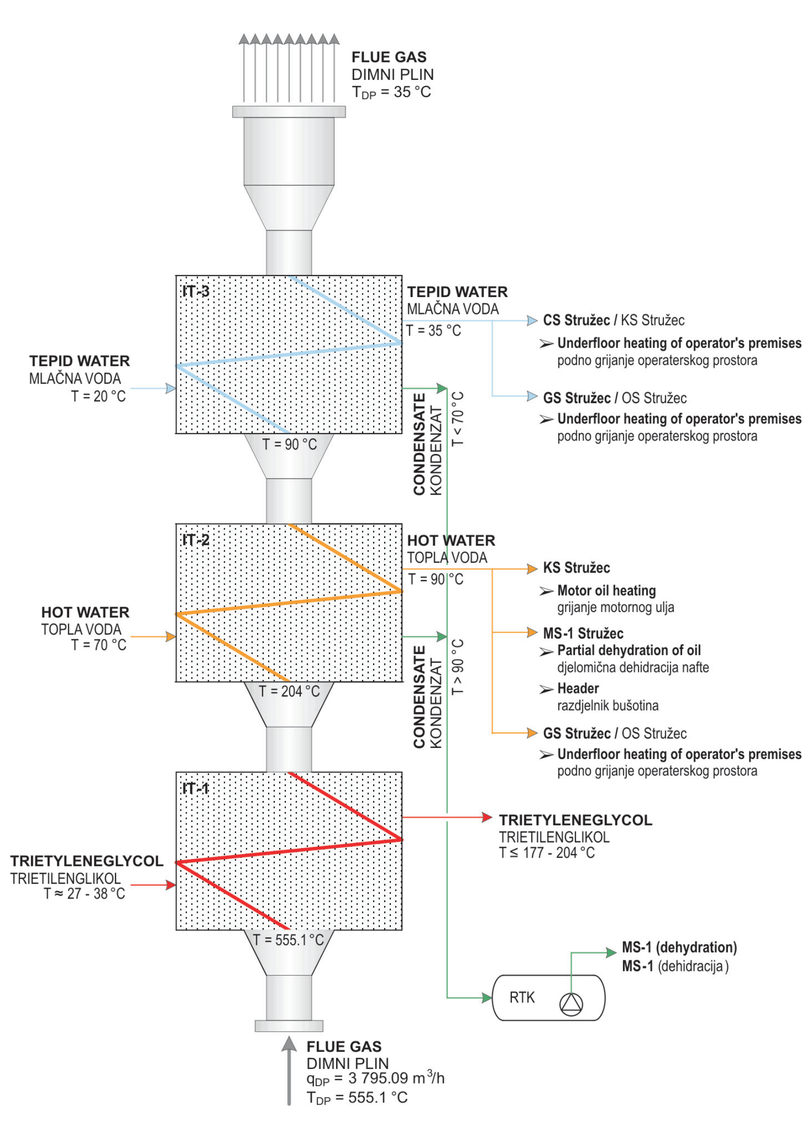

Fig. 3. Schematic presentation of heat exchanger connection for utilization of flue gas heat

Sl. 3. Shematski prikaz spajanja izmjenjivača topline za korištenje topline dimnog plina

L7042G / I-R 4RDS3 x 1 (540 kW) - about 3 000 m³/day of gas

- *CS Šandrovac*
  WAUKESHA L7042GSI / I-R 4RDS3 x 2 (750 kW) - about 4 000 m³/day of gas is used, and on WAUKESHA L7042G / I-R 4RDS3 x 3 (540 kW) - about 3 000 m³/day of gas
- *CS Žutica*
  WAUKESHA L7042G / I-R 4RDS2 x 1 (540 kW) - about 3 000 m³/day of gas is used, and on WAUKESHA F2895GSI / I-R 2RDS2 x 1 (400 kW) - about 2 300 m³/day of gas
- *CS Stružec*
  AUKESHA H24GL / ARIEL JGJ4 x 5 (400 kW; in operation 3 to 4) using about 2 300 m³/day

In case when thermal power of flue gas at CS Stružec is used between maximal temperature of 555,1 °C and minimal temperature of 35 °C, savings of up to 27.95 m³/h of gas or 244 842 m³/year of gas are possible.

Figure 2. is a graphic presentation of interdependence of flue gas thermal power and flue gas temperature at CS Stružec, and Figure 3. is a schematic presentation of heat exchanger connection for utilization of flue gas heat.

5. TECHNICAL AND FINANCIAL EVALUATION OF INVESTMENTS IN CONSTRUCTION OF FLUE GAS HEAT UTILIZATION SYSTEM AT CS STRUŽEC

Flue gas utilization system at CS Stružec includes:

- Three heat exchangers for heating of trietylenglycol (from t_{P1}=27 °C – 38 °C to t_{P2}=177 °C – 204 °C); hot water for dehydration of oil at MS-1, heating of intake collector at GS Stružec (t_{TV1}=70 °C – 90 °C) and tepid water for underfloor heating of operator's premises (t_{MV1}=20 °C – 35 °C),
- Thermally insulated pipelines for connection of heat exchangers to existing installations,
- Circulating centrifugal pump for trietylenglycol, hot water and tepid water,
- Steel structures, supports for heat exchangers,
- Electrical installations, cables and different assemblies,
- Electronic equipment for control, signalling and system operation.

Slightly more than one year would be required for recovery of investments into construction of flue gas utilization system at CS Stružec. In all subsequent years the price of saved gas would be diminished by the price of consumed electricity, which amounts to about 78 000 kn.

It has to be mentioned that system efficiency has not been calculated, which will be done if the proposal is accepted.

Due to reduction in harmful gases emissions, state and European Union stimuli should be used, once the Republic of Croatia becomes a European Union member.

Note: Investment calculation includes costs for supply of equipment, operation and transport.

Evaluation of financial investments:	
1. Preparation of preliminary design and Main project	40 000 kn
2. Preparatory works, surveying documents, obtaining of construction and operating licence	10 000 kn
3. Construction part, foundations for heat exchanger and hot water line supports, earthworks and paving	40 000 kn
4. Mechanical part, heat exchangers, connecting pipelines, steel supports, thermal insulation, anticorrosion protection	550 000 kn
5. Electrical part, circulating centrifugal pumps, distribution cables, distribution boxes	60 000 kn
6. Electronic part, equipment for control, signalling and system operation	55 000 kn
7. Maintenance and electrical power utilization fee	200 000 kn
Grand total	**955 000 kn**

6. CONCLUSION

The Stružec oil field is in the final stage of production. However, in case of use of flue gas heat at CS Stružec, gas savings during one year would be significant. It is quite certain that such quantity of heat would be sufficient for all the requirements at MS-1, GS Stružec and CS Stružec. That solution would certainly extend the field life.

With certain substitution of equipment and process units, such heat would be more than sufficient for MS-1, CS and GS Stružec heating requirements.

It is therefore necessary to make a financial analysis for flue gas heat utilization for all compressor stations on the territory of the Republic of Croatia, which would result in considerable savings of energy and increase production efficiency.

Likewise, it is necessary to make a step in the direction of production cost decrease. In that regard, CROKO process unit at Šandrovac has been in operation for more than 12 years. During that period savings achieved by utilization of heat and electrical energy have been relatively high. Although efficiency of this process unit was confirmed, it is not used on any other field.

Based on results obtained through calculations, it can be concluded that release of flue gases into the atmosphere at CS Stružec results in significant thermal power losses, as illustrated in above calculations.

Accordingly, flu gas at CS Stružec has thermal power of 977 796 kJ/day. That heat is sufficient for heating of trietylenglycol (TEG) in the gas dehydration system. TEG is heated to the temperature of 204 °C in two heaters with 2 x 257 481 kJ installed thermal power.

At CS Stružec thermal power is also used for hot water heating (when temperature drops from 90 °C - 70°C) and to heat in winter period:

- oil in central tank,
- collector and lubricating oil distribution line,
- operator's premises.

Heating of oil in winter period prevents increase of its viscosity. Remaining flue gas heat is sufficient to heat above assemblies at CS Stružec.

In case of utilization of flue gas heat at CS Stružec, savings of 27.95 m^3/h of gas or 244 842 m^3/year would be achieved.

It is also possible to use thermal power of flue gases even below 90 °C. Lower limit can be as low as 35 °C. Such lower thermal power can be used for underfloor heating. When flue gas heat is used below 100 °C, separation of condensed water contained in flue gas must be planned.

If all remaining flue gases thermal power at five remaining compressor stations were to be utilized, total savings are estimates at around $3.25 \cdot 10^6$ m^3/of gas per year.

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