The Exergy Optimisation of the Reverse Combustion Linking in Underground Coal Gasification

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Abstract
Underground Coal Gasification (UCG) is a gasification process carried on in non-mined coal seams using injection and production wells drilled from the surface, which enables the coal to be converted into product gas. A key operation of the UCG is linking the injection and production wells. Reverse Combustion Linking (RCL) is a method of linking the process wells within a coal seam, which includes injection of an oxidant into one well and ignition of coal in the other so that combustion propagates towards the source of oxidant thereby establishing a low hydraulic resistance path between the two wells. The new theory of the RCL in typical UCG conditions has been recently suggested. The key parameters of the RCL process are determined using the technique of Intrinsic Disturbed Flame Equations (IDFE).

This study is concerned with extending the results of the RCL theory to incorporate hydrodynamics of air injection and flow during RCL operation to derive mass flow rate of air to the combustion front as a function of the injection pressure. The results enabled an optimisation procedure maximising the exergy efficiency of RCL process.

Keywords: Underground Coal Gasification (UCG); Reverse Combustion Linking (RCL)

1. Introduction
The UCG is a process of conversion of coal in a coal seam into synthesis gas (syngas) using injection and production wells drilled from the surface. The key step in the development of the underground
reactor is establishing an in-seam link between the injection and production wells which allows production of syngas at commercially significant flow rates.

As described, for example, by Antonova et al.\textsuperscript{1}, several techniques can be used for linking the wells, including the reverse combustion linking (RCL), the directional drilling (DD), hydrofracturing (HF) and the electrolinking (EL). In this paper we focus on the RCL technique. The RCL is a method of linking which includes injection of an oxidant into one well and ignition of coal in the other so that combustion propagates towards the source of oxidant as shown in Fig. 1. The injection of oxidant is maintained until the combustion front reaches the injection well. This is accompanied by a significant drop in the injection pressure indicating creation of a path of low hydraulic resistance between the two wells. Combustion linking is characterized by the speed of linking conventionally measured in meters per day and by air injection rate measured in normal cubic meters per hour.

Fig.1. Schematic view of the Reverse Combustion Linking.

The RCL technique for connecting process wells within the coal seam in underground coal gasification was invented and successfully applied in the USSR at Podmoskovnaya UCG plant in 1941. Since then, RCL was widely used for the well linking in the Soviet UCG plants at Yuzhno-Abinsk (Siberia), Shatskaya and Podmoskovnaya (Moscow Region), Lisichansk (Ukraine) and Angren (Uzbekistan). For example, at Podmoskovnaya the total length of underground channels created by RCL reached 4 - 5 km a year. The method was also utilised in the US UCG program in the 1970s and 1980s. In the European trials\textsuperscript{2}, however, RCL has been used with little success. At the moment, RCL is an integral part of the Exergy UCG technology (εUCG\textsuperscript{TM}), the proprietary UCG technology developed by Ergo Exergy Technologies Inc.

RCL was extensively studied in the Soviet operations. The results of these studies were summarized by Skafa\textsuperscript{3} and Kreinin et al.\textsuperscript{4} The main focus of the studies was on the optimization of the connection speed as a function of the injection rate and the amount of oxidant expended per a unit of the channel length. The analysis of a great wealth of experimental and operational data gathered in the Soviet operations resulted in the empirical laws of RCL that allowed optimization of the process for each
specific UCG plant. No comprehensive theory of RCL, however, was proposed at the time. It is critical for a successful UCG operation that RCL is completed in the shortest possible time and with the minimal energy requirements. This necessitates the development of RCL theory which can be used to optimize the process.

The RCL involves filtration of gases through porous media (coal and surrounding rock) and chemical reactions (oxidation or combustion and reduction). Combination of such processes is generically referred to as Filtration Combustion (FC). The FC has been studied extensively in the literature.

For example, the earlier works by Britten and Krantz\textsuperscript{5,6} and Ohlemiller\textsuperscript{7}, as well as the later studies by Schult et al.\textsuperscript{8,9}, Liu et al.\textsuperscript{10} and Blinderman and Klimenko\textsuperscript{11} are devoted to the reverse FC. The one-temperature model, in which the thermal equilibrium between gas and solid phases is assumed, has been used in most of the previous studies. However, Wahle et al.\textsuperscript{12} studied both the forward and reverse FC in terms of two-temperature model and determined effects of gas-solid non-equilibrium on various aspects of the FC. Stability of the flame front in the FC has also been studied by many authors, including Aldushin and Kasparyan\textsuperscript{13}, Britten and Krantz\textsuperscript{5}, Schult et al.\textsuperscript{9} and Blinderman and Klimenko\textsuperscript{11}.

The FC in the context of the RCL has been previously studied by Britten and Krantz\textsuperscript{5}. The basic assumptions about the RCL mechanism made in their work differed from the reality of the empirical data obtained in applying RCL in UCG operations. Recently, Blinderman and Klimenko\textsuperscript{11} suggested the new theory of the RCL in typical UCG conditions. The theory allows to determine the key parameters of the RCL process by using the technique of Intrinsic Disturbed Flame Equations (IDFE)\textsuperscript{14-16}.

In the present study, the results of the new RCL theory are extended to incorporate hydrodynamics of air flow during RCL operations. A quasi-three-dimensional model of air flow in the process of forming the link is used to estimate the dependence of the mass flow rate of air to the combustion front on the pressure difference between the injection and the production wells. The simplified model, however, retains important physical effects of the real, three-dimensional process, while enabling the usage of the conformal mapping technique.

Since a certain exergy is associated with each unit of air injected in the well during the RCL process, it is commercially important optimise air injection in such a way that results in the minimal exergy consumption rate, which is defined as the amount of exergy spent per unit of the linking distance. The obtained results allow evaluating the optimal regime of the air injection during the RCL operations. This, in turn, leads to an optimisation procedure maximising the Exergy efficiency of the RCL process.

2. The RCL theory

2.1. Review of the RCL theory
Britten and Krantz considered the RCL while solving a set of modelling equations for a planar reverse
combustion front and focusing their attention on the equations for the gas phase. They implicitly assumed deficiency of air and excess of coal in the reaction zone and downstream from it. Although their approach confirmed hydrodynamic instability of the front, which is an important factor in the link formation, the conceptual understanding of the RCL employed by Britten and Krantz contradicts empirical evidence. They consider the RCL as the process of coal pyrolysis followed by combustion of the released volatile matter, so that the hydraulic link between injection and production wells is formed by a porous path of an enhanced permeability. However, empirical data from the UCG operations indicate that the RCL results routinely in formation of a channel, in which coal has been completely (or nearly completely) consumed by combustion.

The observed phenomenon has been recently explained by Blinderman and Klimenko\textsuperscript{11}. We provide only qualitative description of the theory here referring a reader to the previous work\textsuperscript{11} for details. The theory is based of the stability analysis of the reverse FC and the analysis of curved flames and their propagation speed. Special attention is paid to the vicinity of the stoichiometric point in the former, while the latter utilises IDFE.

As discussed in Ref.11, a channel of some “preferred” radius $R_p$ is formed during the RCL, even if the initial conditions correspond to a plane flame. The channel is formed due to instabilities and a variation of coal properties from point to point within a coal seam. At the initial stage of the RCL even several channels could be formed. However, one of them usually “wins” the competition for the gas flow. The radius $R_p$ depends on the total mass flow rate of air $M$ which is a controllable parameter of the RCL process. $R_p$ corresponds to the “preferred” filtration velocity $u_p$, which, in turn, corresponds to the maximum velocity of the flame propagation $s$ as a function of the filtration velocity $u$. As demonstrated by Blinderman and Klimenko\textsuperscript{11}, the “preferred” conditions correspond to the nearly stoichiometric regime.

Unlike the plane flame in the reverse FC, the RCL process in a channel has an internal stabilisation mechanism. The mechanism is based on balancing between narrowing the channel due to instabilities and widening the channel due to decreasing the local propagation velocity of the flame in small cavities. Decreasing of the burning temperature in a disturbed flame due to the flame stretch results in decreasing the velocity of the flame propagation. This effect also contributes to the stabilisation mechanism.

### 2.2 Minimisation of the air consumption rate

The suggested theory enabled to derive the key parameters of the RCL, such as linking speed and radius of the channel, as functions of the total mass flow rate. As a result, the regime of the air injection that corresponds to the minimal air consumption rate, which is defined as the amount of air spent per unit distance of the link, can be estimated. The dependence of the air consumption rate $M_d$ on the total mass flow rate $M$ predicted by the theory (solid line) is presented in Fig. 2. The experimental data obtained in the Chinchilla UCG project are presented by squares, while the optimal point is marked by the cross in Fig. 2.
2.3. Effect of the burn temperature on the channel formation

Another result derived from the RCL theory is the dependence of the channel radius $R_p$ on the burn temperature $T_b$. As shown in Fig. 2, two different regimes are possible for each value of the mass flow rate in the range of interest (upper and lower branches of the curve). These regimes differ in the burn temperature $T_b$ and, therefore, in the channel radius $R_p$. The dependences of the burn temperature and the channel radius on the total mass flow rate are presented in Fig. 3 and Fig. 4, respectively. As in Fig. 2, the crosses in Fig. 3 and Fig. 4 mark the point that corresponds to the minimal air consumption rate. The lower (upper) branch of the curves in Fig. 3 corresponds to the upper (lower) branches of the curves in Fig. 2 and Fig. 4.
As shown in Fig. 4, formation of a narrow channel between injection and production wells, which is interpreted as successful linking, can be achieved only in high-temperature regime. This result of the RCL theory is confirmed by the experience from practical UCG operations.

3. Air flow in typical RCL operations
To perform the exergy analysis of the RCL operations, the relationship between dependence of mass flow rate on the pressure difference between the injection and production wells is required. The dependence is estimated in this section based on the analysis of the air flow through a coal seam during typical RCL process.

3.1. Three-dimensional model
Let us assume that in the RCL operations the tube-like channel of the radius $R_0$ is formed. As illustrated in Fig. 5, at a particular moment, the tip of the channel is at the distance $L$ from the centre of the injection hole of the radius $R_1$, which is drilled throughout of a coal seam of the thickness $B$. Since the flame propagation speed $s$ is significantly lower than the filtration velocity $u$, we assume that the flow is stationary. We also assume and the injected air does not penetrate out of the coal seam, which implies that the pressure gradient is tangential to the coal surface. The coal seam is assumed to be the infinite plate of the thickness $B$, while the channel is assumed to be semi-infinite.
The equations governing the air flow in the coal seam are: the Darcy low

\[ u = -\frac{\kappa}{\mu} \nabla p, \quad (1) \]

the continuity equation

\[ \nabla (\rho u) = 0 \quad (2) \]

and the equation of state for an ideal gas, which can be written in the form

\[ \rho = \frac{m_0}{RT} p. \quad (3) \]

Here, \( u \) is the filtration velocity of air, \( \rho \), \( m_0 \) and \( \mu \) are its density, molar mass and dynamic (or absolute) viscosity respectively. Pressure and absolute temperature are denoted by \( p \) and \( T \), \( \kappa \) is the permeability of coal, and \( R \) is the universal gas constant.

Combining equations (1), (2) and (3) one verifies that the pressure distribution in the coal seam is governed by the following Laplace equation

\[ \frac{m_0 \kappa}{2RT\mu} \nabla^2 p^2 = 0 \quad (4) \]

subject to the boundary conditions:

B.C.1: \( p = p_0 \); in the channel,

B.C.2: \( p = p_1 \); in the hole,

B.C.3: \( \nabla p \cdot n_{cs} = 0 \); at the surface

where \( n_{cs} \) is a unit vector normal to the coal seam. To simplify the further formulae, we use the following notation:
\[ f = -\frac{m_0 \kappa}{2RT\mu} p^2. \quad (6) \]

In terms of the function \( f \) equation (4) becomes

\[ \nabla^2 f = 0, \quad (7) \]

while the boundary conditions (5) transform to

B.C.2: \( f = f_0 = -\frac{m_0 \kappa}{2RT\mu} p_0^2 \); in the channel,

B.C.2: \( f = f_1 = -\frac{m_0 \kappa}{2RT\mu} p_1^2 \); in the hole, \( \quad (8) \)

B.C.3: \( \nabla f \cdot n_s = 0; \) \text{ at the surface}

### 3.2. Quasi-three-dimensional model

It is very difficult, if at all possible, to obtain a rigorous analytical solution of the three-dimensional boundary problem. Meanwhile, under the assumptions that \( L \parallel R_0 \), which is valid for typical RCL operations, the flow is essentially two-dimensional, except for the vicinity of the channel. This allows to estimate the dependence of the mass flow rate on the pressure difference in two steps, while solving two-dimensional problem at each one.

At the first step, it is assumed that the channel is a slit throughout the coal seam. In the plan view, which is schematically presented in Fig. 6, the shape of the channel is assume to be the two-dimensional Rankine half-body. The mass flow rate per unit of the coal seam thickness is expressed as a function of potential difference between the slit-like channel and the injection hole. The value of the potential in the slit-like channel differs from that in the tube-like channel. Then, at the second step, the potential difference between the slit-like and the tube-like channels is estimated, provided that the mass flow rate per unit length of the channel is maintained. The conformal mapping technique is used in both steps.

### 3.2.1. Step 1. Two-dimensional flow in the plane parallel to the coal seam

![Fig.6. The injection hole and the channel (schematic plan view).](image-url)
As shown in Fig 6 and discussed above, the shape of the channel is the Rankine halve body. The radius of the slit-like channel and the potential in the channel are denoted by $R_0$ and $f'_0$, while $R_1$ and $f'_1$ are the radius of the injection hole and the potential in the hole. $L$ is the distance between the tip of the channel and the centre of the injection hole. It is required to find the potential $f$ that satisfies the Laplace equation (7) in the area between the channel and the injection hole and the following boundary conditions

$$
\begin{cases}
  f = f'_0; & \text{in the channel} \\
  f = f'_1; & \text{in the hole.}
\end{cases}
$$

Using the conformal mapping

$$
z_1 = \sqrt{\frac{\pi L}{R_0} - \ln\left(\frac{\pi L}{R_0}\right) - 1},
$$

the area in question in the complex plane $z = x + iy$ (see Fig. 6) is transformed to the right half of the complex plane $z_1$ without the circle of the radius $r_i$, which is the image of the injection hole. The channel is represented by the imaginary axis in the transformed plane, as presented in Fig. 7.

![Fig. 7. The channel and the injection hole in the transformed complex plane.](image)

The centre of the circle is located at distance $l$ from the origin along the real axis, which is expressed as

$$
l = z_1(L + \frac{R_0}{\pi}) = \sqrt{\frac{\pi L}{R_0} - \ln\left(\frac{\pi L}{R_0}\right) + 1}. \quad (11)
$$

The radius of the circle is estimated as

$$
r_i = z_1(L + \frac{R_0}{\pi} + R_1) - z_1(L + \frac{R_0}{\pi}) \approx \left. \frac{dz_1}{dz} \right|_{L + \frac{R_0}{\pi}} \cdot R_1, \quad (12)
$$
where
\[
\frac{dz_1}{dz} = \frac{\pi z - R_0}{2R_0^2z^2 - \ln \left( \frac{\pi z}{R_0} \right) - 1}.
\] (13)

Using Eqs. (r def) and (dzz) one verifies that
\[
r_i \approx \frac{\pi^2L}{2IR_0(\pi L + R_0)} R_i
\] (14)

The required complex potential \( F_1(z_i) \) is the well-known potential of a source of the strength \( 2\pi C_1 \) located at \((l + i \cdot 0)\) and a sink of the equivalent strength located at \((-l + i \cdot 0)\):
\[
F_1(z_i) = C_1 \ln \left( \frac{z_i - l}{z_i + l} \right) + C_2.
\] (15)

Note that the strength of the source and sink is the mass flow rate per unit of the coal seam thickness \( M/B \). The constants \( C_1 \) and \( C_2 \) are determined from the boundary conditions (9) as follows:
\[
\text{Re}(F_i(0)) = f'_0 \quad \Rightarrow \quad C_2 = f'_0
\] (16)
and
\[
\text{Re}(F_i(l + r_i)) = f_1.
\] (17)

In typical UCG conditions, \( l \ll r_i \) and, therefore, \( 2l + r_i \approx 2l \). Then, the constant \( C_1 \) is estimated from equation (17) as
\[
C_1 \approx \frac{f_1 - f'_0}{\ln \left( \frac{l}{2l} \right)},
\] (18)
and equation (15) reads as
\[
F_1(z_i) = \frac{f_1 - f'_0}{\ln \left( \frac{l}{2l} \right)} \ln \left( \frac{z_i - l}{z_i + l} \right) + f'_0.
\] (19)

The mass flow rate of air per unit of the coal seam thickness \( M/B \) is then expressed as
\[
\frac{M}{B} = \frac{2\pi(f_1 - f'_0)}{\ln \left( \frac{l}{2l} \right)}.
\] (20)

Rigorously, the image of the injection hole under the mapping (10) differs from the circle of the radius \( r_i \). The same is true for the equipotential curve corresponding to \( f_1 \). However, the differences are
negligibly small for typical UCG conditions.

3.2.2. Step 2. Two-dimensional flow in the surface perpendicular to the coal seam

Now consider a second two-dimensional flow in the surface, which is generated by shifting a particular streamline of the first flow in the direction perpendicular to the plane of the first flow (see Fig. 8). In the case of the slit-like channel, the flow is uniform, as is presented in Fig. 8. The complex potential $F'_2$ of the flow is expressed as

$$F'_2(z) = \pm \frac{\dot{m}}{2B} z + C_3. \quad (21)$$

Here, $\dot{m}$ is the flow rate per unit length of the channel, the sign “-” is used on the left of the channel, and the sign “+” is used on the right.

![Fig. 8. The schematic section view of the slit-like channel.](image)

To obtain the complex potential $F_2$ of the flow in the case of the tube-like channel, note that the conformal mapping

$$z_2 = \sinh \left( \frac{\pi z}{B} \right) \quad (22)$$

maps the strip of the width $B$ on the entire plane. The radius of the channel $R_0$ is small compared to the coal seam thickness $B$ in typical RCL operations. In this case, the difference between the image of the channel and a circle is negligibly small. Then, the complex potential $F_2$ is expressed as

$$F_2(z) = \frac{\dot{m}}{2\pi} \ln \left( \sinh \left( \frac{\pi z}{B} \right) \right) + C_4. \quad (23)$$

The streamlines of the flow in the case of the tube like channel is schematically presented in Fig. 9.
Fig. 9. The schematic section view of the tube-like channel.

The potentials $F'_{22}$ and $F_{22}$ are assumed to be the same far apart from the channel \( \lim_{F \to \infty} (F_{22}(z) - F'_{22}(z)) = 0 \), which implies that

\[
C_3 = C_4 = \frac{m}{2\pi} \ln(2). \tag{24}
\]

Then, the difference \( f_0 - f'_0 \) of the potentials in the tube-like and slit-like channels is expressed as

\[
f_0 - f'_0 = \text{Re}(F_{22}(R_0)) - \text{Re}(F'_{22}(R_0)) \approx \frac{m}{2\pi} \left( \ln(r_0) - r_0 + \ln(2) \right), \tag{25}
\]

where

\[
r_0 = \frac{\pi R_0}{B}. \tag{26}
\]

Substituting equation (25) in equation (20) gives

\[
\frac{M}{B} = 2\pi \left[ \left. f_1 - f_0 + \frac{m}{2\pi} \left( \ln(2r_0) - r_0 \right) \right| \right] \tag{27}
\]

The flow rate \( \dot{m} \) per unit of the channel length is estimated using the flow considered in Step 1 (see Section 3.2.1.) as follows

\[
\frac{\dot{m}}{2\pi} = \text{Re} \left( \frac{dF_1}{dz_1} \right) \bigg|_{z_1 = \tilde{y}}, \tag{28}
\]

where

\[
\frac{dF_1}{dz_1} = \frac{f_1 - f'_0}{\ln\left(\frac{r_0}{R_0}\right)} \frac{2l}{z_1^2 - l^2}, \tag{29}
\]
and the adjustable parameter $\gamma$ is a point on the imaginary axis in the complex plane $z_i$. The parameter is selected to reproduce the experimental data obtained in the Chinchilla UCG project.

Using equations (20), (28) and (29) one verifies that

$$\dot{m} = -\frac{LM}{\pi B(\gamma^2 + l^2)}.$$  \hspace{1cm} (30)

Substituting the above equation in equation (27) gives

$$\frac{M}{B} \left[1 + \frac{2l(\ln(2r_0) - r_0)}{(\gamma^2 + l^2) \ln(\frac{\gamma}{2l})} \right] = \frac{2\pi(f_1 - f_\circ)}{\ln(\frac{\gamma}{2l})}.$$ \hspace{1cm} (31)

Finally, recalling the expressions $f_1$ and $f_\circ$ given by equation (8), the following equation that relates the total mass flow rate $M$ and the key parameters of the RCL process, such as the coal permeability, radii of the injection hole and the channel, the distance between them and pressure values in the hole and in the channel, can be obtained:

$$\frac{M}{B} \left[1 + \frac{2l(\ln(2r_0) - r_0)}{(\gamma^2 + l^2) \ln(\frac{\gamma}{2l})} \right] = -\frac{\pi m_o \kappa (p_1^2 - p_\circ^2)}{RT \mu \ln(\frac{\gamma}{2l})}.$$ \hspace{1cm} (32)

The above equation enables estimating the exergy efficiency of the RCL operations being incorporated in the previously developed RCL theory$^{11}$.

### 4. Exergy optimisation

However, the minimum of the air consumption rate $M_a$ does not necessarily correspond to the minimum of the exergy consumption rate $Ex_a$. Other factors should also be taken into account. For example, it could be exergy inefficient to maintain the total mass flow rate required for the optimal $M_a$, if the coal permeability $\kappa$ is small.

In a gas compression process, the exergy change per one mole of ideal gas is expressed$^{17}$ as

$$Ex_m = c_p (T - T_{am}) - T_{am} \left[ c_p \ln \left( \frac{T}{T_{am}} \right) - R \ln \left( \frac{p}{p_{am}} \right) \right].$$ \hspace{1cm} (33)

where $c_p$ is the heat capacity of the gas at constant pressure, $T_{am}$ and $p_{am}$ are ambient temperature and pressure, while $T$ and $p$ are final temperature and pressure$^{17}$. In typical RCL operations, $T_{am} = 300 \text{ K}$ and $p_{am} = 1 \text{ atm}$, while the injection pressure $p = p_i$ is an order of 30 atm, while the final temperature $T$ depends on the type of compressors used.

In the following, we neglect the temperature change in the air compression to make the analysis
independent of the type of the equipment. In this case, the exergy change per one mole of air is expressed as

\[ Ex_m = RT_{am} \ln \left( \frac{p}{p_{am}} \right) \] (34)

However, using the more general equation (33) instead of equation (34), the compressor characteristics could also be taken into account.

The calculations of the exergy efficiency have been performed for typical UCG conditions. The pressure difference between the injection and production wells required to maintain a particular total air flow rate has been calculated using the quasi-three-dimensional model. The results are presented in Fig. 10. In this figure the air injection regime that corresponds to the minimal exergy consumption rate is marked by the circle, while the cross represent the regime with the minimal air consumption rate. As shown in Fig. 10, the regime with the minimal air consumption is not exergy-optimal, and it is more exergy-efficient to inject air with smaller total air flow rate.

![Fig.10. Exergy consumption rate as a function of the total mass flow rate.](image)

5. Conclusions

The recently suggested RCL theory allows estimation of the regime that corresponds to the minimal air consumption rate and explains the experimentally confirmed necessity to perform the linking at high temperature.

The proposed quasi-three-dimensional model enabled estimation of the dependence of the air mass flow rate on the pressure difference between the injection and production wells. As a result, the exergy-efficient regime can be estimated based on the previously developed RCL theory.
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