Thermal and bifurcation characteristics of heat-recirculating conversion of gaseous fuels

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Abstract  The paper investigates the possibility of utilisation of heat-recirculating systems for fuel conversions having low net thermal effect. The experimental part is conducted with an electrically heated heat exchanger. It is shown that heat-recirculating systems can operate under superadiabatic conditions. Their thermal characteristics are provided by means of the dependencies of heat recirculation ratio on process parameters. Further, the heat-recirculating catalytic combustion system is characterised via combustion bifurcation diagrams. The similarities and differences of both those heat-recirculating systems are qualitatively compared and explained. Bifurcation characteristics proves to be useful tools in concise description of practical complex heat-recirculating fuel conversion systems in energy generation.

Keywords: Heat-recirculating system; Conversion of gaseous fuels; Thermal integration

Nomenclature

\[ C_P \] specific heat, J kg\(^{-1}\) K\(^{-1}\)
\[ E \] enthalpy stream, J s\(^{-1}\)
IGCC internal gasification combined cycle
HYPOGEN H\(_2\) power generation
\[ L \] heat losses ratio
\[ m \] mass flow rate of the gas, kg s\(^{-1}\)

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1 Introduction

Generation of energy from gaseous fuels with fuel to electricity efficiency exceeding 35–40% requires novel technological, material and engineering approaches. Additional complexity for this task arises from strict environmental requirements for energy generators. Heat-recirculating systems for combustion of low-calorific gaseous fuels offer increased thermal efficiency and the reduction of emissions of harmful substances [1]. Heat-recirculating systems can utilize recuperative heat exchange. When heat recirculation is sufficiently intensified beneficial superadiabatic conditions can be attained, i.e. $\Delta T$ in the combustor can be several times higher than $\Delta T$ of the adiabatic combustion process. The combustion literature reports several kinds of practical heat-recirculating burners. Namely, a spiral “Swiss roll” heat-recirculating device which has found application in micro-combustors [2]. At small scales heat and friction losses become more significant thus the utilization of devices based on existing macro-scale systems such as IC engines which have moving parts and produce hot exhaust gases may be impractical. Therefore, other novel approaches to electricity generation including those based on thermoelectric, pyroelectric, electrochemical and thermophotovoltaic phenomena can be used in conjunction with heat-recirculating combustors.

Modern energy and fuel processing technologies need thermally integrated systems in order to meet demanding energy efficiency requirements. Heat-recirculating and superadiabatic processes are inevitable in such energy technologies and therefore they require intensive research efforts in order to better understand its process and thermodynamic features. Recirculating combustion processes are typically characterised by bifurcation
Thermal and bifurcation characteristics of heat-recirculating conversion. Therefore, in the current article thermal and bifurcation characteristics of heat-recirculating conversion of gaseous fuels are provided.

2 Thermal characteristics

Experimental studies of heat-recirculating systems are realized via a setup presented schematically in Fig. 1. Namely, the incoming air having temperature $T_{IN}$, is injected into recuperator’s channels by means of a fan. In the recuperator air is heated up to temperature $T_R$. A spiral heater having an adjustable power $P_H$ is mounted downstream which further heats the gas to the temperature $T_H$. The gas is then recycled back into the heat exchanger and exits the system having temperature $T_{OUT}$. A gas flow rate $m$, temperatures $T_{IN}$, $T_{OUT}$, and $T_H$ so as a voltage supplied to the spiral heater are collected.

![Figure 1. The scheme of the investigated heat-recirculating system.](image)

The experimental results are interpreted by means of quantities defined below:

- heat losses to surroundings:
  \[
  \dot{Q}_L = P_H + \dot{E}_{IN} - \dot{E}_{OUT};
  \]

- heat recuperated in the heat exchanger:
  \[
  \dot{Q}_R = \dot{E}_H - \dot{E}_{OUT};
  \]

- quotients:
  \[
  L = \frac{\dot{Q}_L}{P_H}, \quad R = \frac{\dot{Q}_R}{P_H}, \quad R^{AD} = \frac{\dot{Q}_R}{P_H - \dot{Q}_L}.
  \]
Stream $E$ is evaluated as:

$$
\dot{E} = \dot{m} C_P T, \quad (4)
$$

where $C_P$ is the specific heat of humid air (a typical value of $X$ in the present experiments equals $5 \cdot 10^{-3}$ kg water kg dry air$^{-1}$):

$$
C_P = 1005 + X \cdot 1930 \approx 1015. \quad (5)
$$

During experiments the temperatures are varied from 15 to 50 °C, $m$ from 0 to 0.08 kg s$^{-1}$, and $P_H$ from 0 to 210 W. A sample of experimental results is presented in Tabs. 1–3.

Table 1. The effect of the power of the heater $P_H$ on heat recirculation, $m = 0.0235$ kgs$^{-1}$.

| No. | $P_H$ [W] | $T_{IN}$ [°C] | $T_H$ [°C] | $T_{OUT}$ [°C] | $Q_L$ [W] | $Q_R$ [W] | $L$ [-] | $R$ [-] | $R^{AD}$ [-] |
|-----|-----------|----------------|-------------|-----------------|----------|----------|--------|--------|------------|
| 1   | 52.5      | 17.0           | 20.1        | 17.6            | 37       | 63       | 0.7    | 1.2    | 4          |
| 2   | 72.3      | 17.1           | 21.2        | 17.7            | 58       | 83       | 0.8    | 1.2    | 6          |
| 3   | 86.8      | 17.2           | 24.3        | 18.1            | 63       | 147      | 0.7    | 1.7    | 6          |
| 4   | 105       | 17.2           | 26.4        | 18.2            | 81       | 200      | 0.8    | 1.9    | 8          |
| 5   | 122       | 17.4           | 30.4        | 18.7            | 91       | 278      | 0.7    | 2.3    | 9          |
| 6   | 141       | 18.4           | 38.0        | 20.2            | 95       | 458      | 0.7    | 3.2    | 10         |
| 7   | 143       | 18.2           | 37.5        | 20.4            | 85       | 451      | 0.6    | 3.2    | 8          |
| 8   | 148       | 17.3           | 36.7        | 19.1            | 101      | 453      | 0.7    | 3.0    | 10         |
| 9   | 159       | 17.4           | 39.0        | 19.5            | 106      | 489      | 0.7    | 3.1    | 9          |
| 10  | 178       | 17.7           | 44.8        | 20.1            | 121      | 586      | 0.7    | 3.3    | 10         |

From Tab. 1 it can be observed that for a constant mass flow rate of air ($m = const.$) $Q_L$ slightly increases with rising $P_H$ while $L$ is stable in the whole range of $P_H$. $Q_R$ and $R$ increase with rising $P_H$. From Tab. 2 it is seen that for a constant power ($P_H = const.$) $Q_L$ and $L$ drop with rising $m$. $Q_R$ and $R$ increase with rising $m$. In total combustion of gaseous mixtures with constant concentration the combustion heat released per kg of the gas is constant. Such relation holds for the results presented in Tab. 3 which will be discussed in more details. From Tab. 3 it is seen that for $P_H/m = const.$, $Q_L$ is relatively stable in the whole range of $m$ while $L$ considerably drops with rising $m$. Both $Q_R$ and $R$ considerably increase with rising $m$. The dependencies for $P_H/m = const.$ are further presented in Figs. 2–4.

Figure 2 shows that heat transfer in the heat exchanger $Q_R$ considerably increases with rising $m$ while heat losses to the surroundings $Q_S$ are smaller.
Table 2. The effect of the mass flow rate of air $m$ on heat recirculation, $P_H = 142.5 \, \text{W}$.

| No. | $m$ [kg/s] | $T_{IN}$ [°C] | $T_H$ [°C] | $T_{OUT}$ [°C] | $Q_L$ [W] | $Q_R$ [W] | $L$ [-] | $R$ [-] | $R^{AD}$ [-] |
|-----|-------------|---------------|-----------|----------------|---------|---------|-------|------|-----------|
| 1   | 0.0152      | 18.4          | 40.8      | 21.2           | 99      | 302     | 0.7   | 2.1  | 7         |
| 2   | 0.0253      | 17.3          | 36.7      | 19.1           | 101     | 453     | 0.7   | 3.0  | 10        |
| 3   | 0.0253      | 18.4          | 38.0      | 20.2           | 95      | 458     | 0.7   | 3.2  | 10        |
| 4   | 0.0260      | 18.2          | 37.5      | 20.4           | 85      | 451     | 0.6   | 3.2  | 8         |
| 5   | 0.0323      | 18.2          | 35.1      | 19.8           | 89      | 502     | 0.6   | 3.5  | 10        |
| 6   | 0.0412      | 18.0          | 32.5      | 20.0           | 59      | 522     | 0.4   | 3.7  | 6         |
| 7   | 0.0621      | 18.1          | 28.0      | 19.2           | 74      | 554     | 0.5   | 3.9  | 8         |
| 8   | 0.0671      | 17.7          | 26.5      | 19.2           | 34      | 497     | 0.3   | 3.6  | 5         |

and relatively stable. This behaviour is attributed to superior performance of the heat recirculating system at higher $m$. The beneficial behaviour is well seen also in Fig. 3. $R$ increases with rising $m$ while $L$ drops. The dependence of $R$ on $m$ is linear at least for values of $m$ ranging from 0.015 to 0.075 kg s$^{-1}$.

Finally, Fig. 4 shows that adiabatic heat recirculation ratio $R^{AD}$ is higher than $R$ and also rises with rising $m$. However, the observed rise of $R^{AD}$ is less pronounced at higher values of $m$. This result arises from the definition of $R^{AD}$, Eq. (4). Namely, for $P_H/m = \text{const.}$, $Q_L$ is stable while $Q_R$ considerably increases with rising $m$ leading to the rise of $R$. For
smaller $m$, $Q_R$ is comparable in value with $Q_L$ and hence $Q_L$ decreases the denominator of $R^{AD}$. For smaller $m$ we thus have $R^{AD} \gg R$. On the other hand, at higher values of $m$, $Q_R$ is large compared with $Q_L$ (see Fig. 2). Consequently, as it can be observed in Fig. 4, the functions $R^{AD}(m)$ and $R(m)$ gradually coincide while $m$ rises.
Figure 4. The dependence of $\log R^{AD}$ and $\log R$ on $m$, $P_H/m = 2735$ J kg$^{-1}$.

3 Bifurcation characteristics

Heat-recirculating systems are well-suited for fuel conversion processes having a low net thermal effect, e.g. combustion of lean gases [3], oxidative reforming of hydrocarbons (combines endo- and exothermic reactions) or biomass gasification [4–5]. However, behaviour of such reactive systems is more complicated than that of the system with the electrical heater examined in Section 2. In reacting systems, new physical phenomena linked with oxidation reactions and relevant heat release must be carefully taken into account. Firstly, a combustion energy release can take place when combustor’s temperature is sufficiently high, such that oxidation reactions (current work relates to surface reactions) can be activated. Secondly, as the combustion heat release now replaces an electrical heater the behaviour of the heat recirculating system becomes more complex due to mass transport and surface reaction effects. Thirdly, in superadiabatic combustion, under complete conversion conditions, the power $P_H$ is proportional to the flow rate $m$ which holds only for the results presented in Tab. 3 and in Figs. 2–4. For extremely low $m$ the power of the system is too low and the combustion can not be self-sustained due to e.g. an axial conduction effect. On then other hand, for higher $m$ the rate of the catalytic reaction is mass transport limited thus reduces conversion and also leads to extinction.
Such types of complexities are the main reason of bifurcation behaviour of heat-recirculating reaction systems. Bifurcation behaviours are quite common in reaction systems and especially in combustion systems. Recently, interesting complex bifurcations (flame dynamics – dancing flames) have been reported for hydrogen flames in microchannels for a simple non-heat-recirculating combustor [6].

The similarities and differences between the results for the heat-recirculating system presented in Section 2 and previous numerical investigations of the author’s research group on the heat-recirculating catalytic combustion system [7] are briefly summarised below. Heat-recirculating combustion examined in [7] utilises a catalytic recuperative reactor in which heat recirculates in a similar fashion as in the heat-recirculating system from Fig. 1. However, a radial dimension of the system examined in [7] is substantially reduced, i.e. it is typical for high-efficiency (both in heat [8–9] and mass transfer) microreactor and therefore the systems are compared qualitatively and not quantitatively.

The phenomena of combustion bifurcations revealed in the author’s recent work [7] are now classified into three general kinds. The first one is an isola (Fig. 5), the second is a hysteresis (Fig. 6) and the third one is a bifurcation with pressure as the bifurcation parameter (Fig. 7). When a gas flow rate \( m \) is used as the bifurcation parameter the combustor exhibits an isola bifurcation. The isola is characterised by the existence of two extinction folds, Fig. 5. The ignited combustor can operate for values of \( m \) inside the isola loop. Besides, the ignition is not possible by varying only the flow rate parameter but the change in the flow rate can extinguish the oxidation reaction when the values from outside the isola loop are utilised. In Fig. 5 it can be observed that maximal \( R (\sim 30) \) within the isola loop is attained for \( m_{max} \approx 1.7 \cdot 10^{-6} \text{ kg s}^{-1} \).

From comparison of Fig. 5 and Fig. 3 it is seen that behaviours of the heat recirculating system from Fig. 1 and the heat-recirculating combustion system investigated in [7] are quite different. Main difference is linked with extinction phenomena. For low values of \( m \) the adverse effects of reduced power and axial conduction lead to the reduction of temperature which degrades conversion and hence the combustion system extinguishes. More interesting is the explanation for the extinction fold for higher \( m \). It can be observed in Fig. 3 and in Tab. 3 that at higher \( m \) both \( R \) and \( T_H \) are high. Heat transfer is not degraded at higher values of \( m \) and the power \( P_H \) rises with rising \( m \). Thus the extinction can not be attributed to reduced power,
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Figure 5. Heat-recirculating combustion – isola bifurcation.

Degraded heat transfer or reduced $P_H$. A concise explanation must address mass transport. It is important that the superadiabatic reactor of [7] is catalytic, i.e. combustion reaction proceed at the catalytic surface located at the reactor’s walls. At higher $m$ the gas velocity also increases and thus mass transport limitations occur. Since diffusion is a weak function of temperature the increased power does not play a significant role in increasing of mass transport limited combustion rates. Consequently, at higher $m$ a part of reactants can not diffuse to the catalytic surface, conversion drops and extinction phenomenon is exhibited.

Further, when the reactor inlet temperature is used as the bifurcation parameter the reactor exhibits a hysteresis bifurcation. The hysteresis is characterised by the existence of ignition and extinction folds, Fig. 6. The extinction fold is typically located below the ambient temperature ($\sim 300$ K) and the oxidation of lean fuels can be self-sustained, i.e. autothermal. A cold combustor can be ignited only if its gas inlet temperature exceeds the ignition temperature, i.e. is above the temperature of ignition fold ($\sim 480$ K in Fig. 6).

Furthermore, from comparison of Figs. 5 and 6 it can be concluded that the investigated system offers more fuel flexible conversion of gases. For instance, when high heating value fuels are converted (resulting in a high
reactor temperature) the gas can be passed through the reactor with a different flow rate so as to decrease the reactor temperature. The direction of the required change in \( m \) depends on the actual process location on the isola bifurcation diagram, i.e. when actual \( m < m_{\text{max}} \) the flow rate \( m \) should be decreased and when actual \( m > m_{\text{max}} \) the flow rate \( m \) should be increased. Consequently, thermal stabilisation of the reactor and increased fuel flexibility can be attained via advanced process control [10].

![Figure 6. Heat-recirculating combustion - hysteresis bifurcation.](image)

Bifurcations with pressure as the bifurcation parameter which have recently been reported in [7] are characterised by the existence of one extinction fold, Fig. 7. When the pressure of the system is reduced the combustor can extinguish. However, at relatively high-pressure ratios no extinction is observed which further contributes to stable operation of the heat-recirculating high-pressure systems, e.g. gas turbine combustors [7].

Bifurcation behaviour of superadiabatic processes depends on reactor geometry and its operational conditions. The type of bifurcation, the shape of its diagrams or the location of its folds can strongly vary depending on those design factors. The changes can have important practical consequences such as a decreased ignition temperature, combustion stability, fuel flexibility, increased gas throughputs and heat recirculation ratios. Besides, bifurcation analyses provide a simple tool for improved understanding and thermal integration of complex novel heat and mass-recirculating energy systems including those based on SOFCs [11–12] and other HYPOGENs [13]. Namely,
small scale SOFCs (< 1 kW) require thermally efficient solutions to attain above 700 K in a fuel reformer [14]. Similarly, by using heat recirculation, smaller scale power plants can avoid a substantial drop in its fuel to electricity efficiencies, especially those operated in the IGCC [15] mode, involving CO₂ capture processes [16–17] or involving waste-to-energy systems [18].

The recirculation of heat and mass is frequently used in newly developed modern gas-based energy generation systems. Thus, the results of the current thermal and bifurcation analyses of heat-recirculating systems will help to understand, predict and control such complicated modern energy systems.

4 Summary

The experimental results for thermal characteristics of the heat-recirculating systems were reported. It was shown that heat-recirculating systems can operate under superadiabatic conditions. Such systems were especially useful in combustion of low-calorific gaseous fuels or in other low heating value fuel conversions, e.g. in oxyforming. The superadiabatic combustion enabled more energy efficient, fuel flexible and environmentally friendly conversion of gaseous fuels. The described bifurcations allowed reliable qualitative

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Figure 7. Heat-recirculating combustion – bifurcation with pressure as the bifurcation parameter.
and quantitative analysis of practical heat-recirculating systems, especially those relating to novel fuel conversion energy technologies.

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