archives
of thermodynamics
Vol. **31**(2010), No. 2, 63–75
DOI: 10.2478/v10173-010-0009-6

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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m_{max} – m at which maximal temperature is attained within isola loop, kg s^{-1}
P – pressure, Pa
P_H – power of the system, W
Q_L – heat losses to the surroundings, J s^{-1}
Q_R – heat stream in the recuperator, J s^{-1}
R – heat recirculation ratio
R^{AD} – adiabatic heat recirculation ratio
SOFC – solid oxide fuel cell
T – temperature, K
T_{OUT} – outlet temperature, K
T_{IN} – inlet temperature, K
T_H, T_R – temperatures (see Fig. 1), K
X – content of water in air, kg water kg dry air^{-1}

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. ΔT in the combustor can be several times higher than ΔT 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 behaviour. 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 set-up 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.

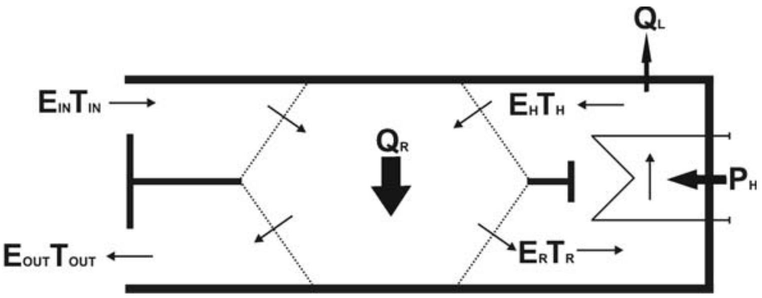

Figure 1. The scheme of the investigated heat-recirculating system.

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

heat losses to surroundings:

$$\dot{Q}_L = P_H + \dot{E}_{IN} - \dot{E}_{OUT} \; ; \tag{1}$$

heat recuperated in the heat exchanger:

$$\dot{Q}_R = \dot{E}_H - \dot{E}_{OUT} \; ; \tag{2}$$

quotients:

$$L = \frac{\dot{Q}_L}{P_H} \; , \quad R = \frac{\dot{Q}_R}{P_H} \; , \quad R^{AD} = \frac{\dot{Q}_R}{P_H - \dot{Q}_L} \; . \tag{3}$$

Stream E is evaluated as:

$$\dot{E} = \dot{m} C_P T \;, \tag{4}$$

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}):

$$C_P = 1005 + X \cdot 1930 \approx 1015 \;. \tag{5}$$

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	72.1	17.1	21.2	17.7	58	83	0.8	1.2	6
3	86.8	17.1	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, $P_H = 142.5$ 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

Table 3. The effect of the mass flow rate of air m on heat recirculation, $P_H/m = 2735$ J kg^{-1}.

No.	m [kg/s]	T_{IN} [°C]	T_H [°C]	T_{OUT} [°C]	Q_L [W]	Q_R [W]	L [–]	R [–]	R^{AD} [–]
1	0.0095	17.6	18.4	17.9	25	5	0.9	0.2	2
2	0.0158	17.6	19.4	18.0	35	23	0.8	0.5	3
3	0.0196	17.7	20.1	18.1	44	40	0.8	0.8	4
4	0.0222	17.6	20.7	18.2	45	56	0.8	1.0	4
5	0.0253	17.6	21.7	18.3	53	89	0.8	1.3	5
6	0.0317	17.7	23.1	18.6	56	145	0.7	1.7	5
7	0.0507	17.9	28.4	19.2	75	473	0.5	3.3	7
8	0.0570	17.8	29.6	19.2	76	599	0.5	3.8	7
9	0.0633	17.9	31.7	19.6	67	775	0.4	4.4	7
10	0.0678	17.9	32.4	19.6	65	881	0.4	4.7	7

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 $P_H/m = const.$, Q_L is stable while Q_R considerably increases with rising m leading to the rise of R. For

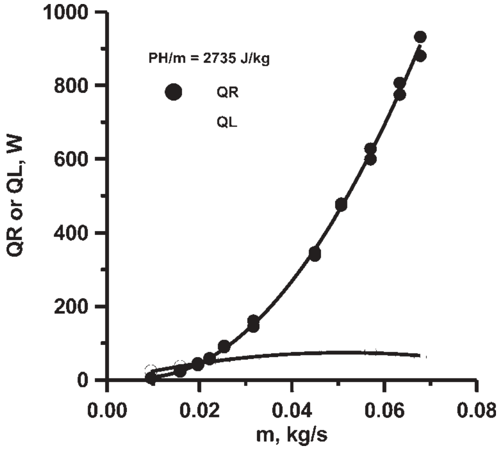

Figure 2. The dependence of Q_L and Q_R on m, $P_H/m = 2735$ J kg^{-1}.

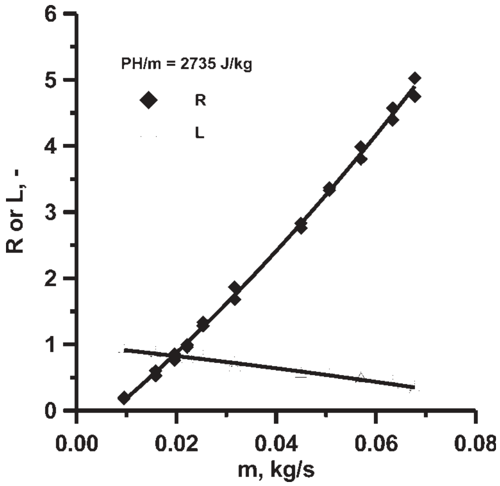

Figure 3. The dependence of R and L on m, $P_H/m = 2735$ J kg^{-1}.

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 $R^{AD} >> R$. 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.

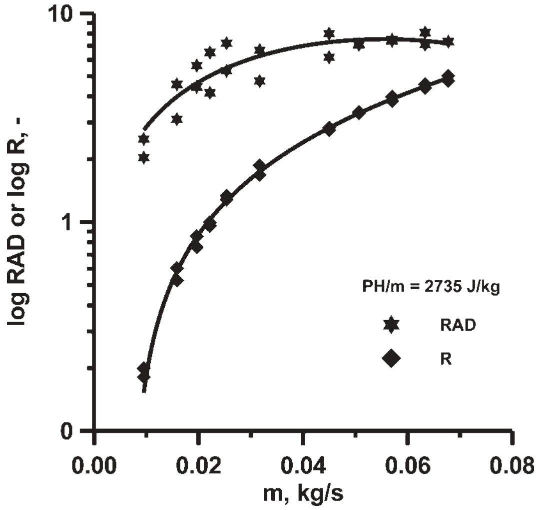

Figure 4. The dependence of log R^{AD} and log R on m, $P_H/m = 2735$ J kg^{-1}.

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 (~ 30) within the isola loop is attained for $m_{max} \approx 1.7 \cdot 10^{-6}$ 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,

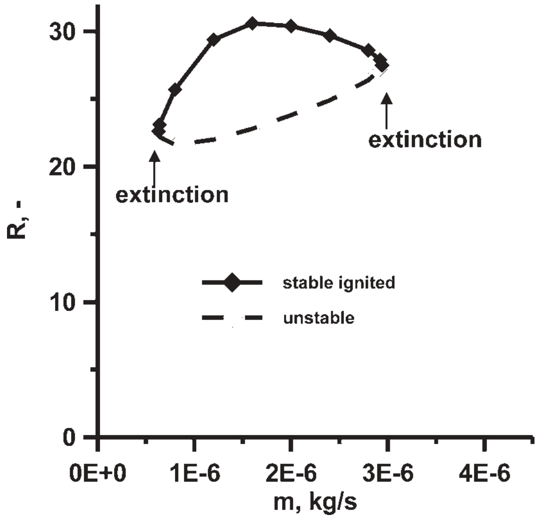

Figure 5. Heat-recirculating combustion – isola bifurcation.

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 $m < m_{max}$ the flow rate m should be decreased and when actual $m > m_{max}$ 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].

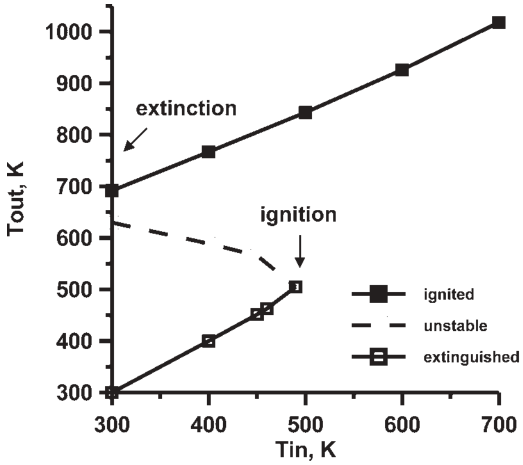

Figure 6. Heat-recirculating combustion - hysteresis bifurcation.

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,

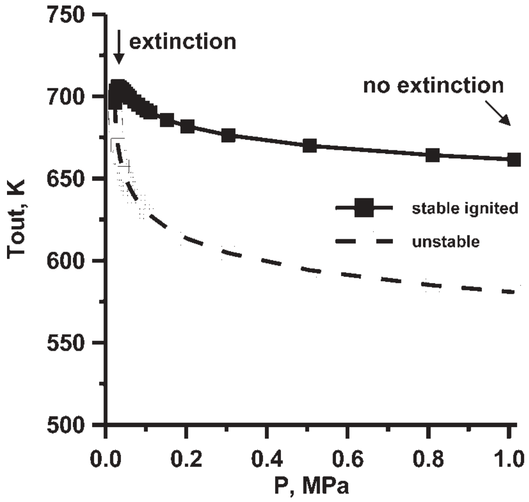

Figure 7. Heat-recirculating combustion – bifurcation with pressure as the bifurcation parameter.

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 CO_2 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 and quantitative analysis of practical heat-recirculating systems, especially those relating to novel fuel conversion energy technologies.

Acknowledgements The financial contribution of Wrocław University of Technology (Poland) under the grant number 332116/2008 is gratefully acknowledged.

Received 25 September 2009

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