Experimental Research on the Thermal Oxidation of Ventilation Air Methane in a Thermal Reverse Flow Reactor

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ABSTRACT: The thermal reverse flow reactor is an effective technical equipment for dealing with ventilation air methane, which has been causing a significant greenhouse effect. An experimental study on the thermal oxidation of ventilation air methane in a thermal reverse flow reactor was conducted. A mixture of domestic gas and ambient air was used to simulate ventilation air methane in the experiments, and the methane conversion efficiency was analyzed based on the concentration of combustion products determined by gas chromatography equipment. In addition, the effects of the switching time, the inlet methane concentration, the flow rate, and heat extraction were studied. The experimental results show that the reverse flow reactor system can run under a wide range of operating conditions with autothermal operation and high methane conversion. In addition, this system can even work with methane concentrations as low as 0.30% in the autothermal operation mode without NOx emission. Unlike previous studies, this study shows that the flow rate has little effect on the methane conversion rate in the cyclic steady state over a wide range of operating conditions. In addition, methane conversion and reaction zone change as the inlet methane concentration varies during the reaction process in the cyclic steady state. The combined optimization of operating parameters can effectively improve the stability of the reverse flow reactor system and methane conversion efficiency.

1. INTRODUCTION

A large quantity of methane is discharged into the air from coal mines each year, 70% of which is emitted by ventilation air methane (VAM)—methane emitted with mine venting flow, with more than 20 billion cubic meters per year in China.1 In addition to the environmental issue, as a kind of gas fuel, coal mine methane (CMM) emission also causes waste of energy resources. Three types of CMM exist: (1) VAM, with a methane concentration of 0.1−1%; (2) methane drained from the seam before mining, with a methane concentration of 60−95%; and (3) methane from worked areas of the mine, usually with a methane concentration of 30−95%.2 Because VAM contributes most emissions to the atmosphere from gassy coal mines,3 how to collect and utilize the VAM in an efficient way has great significance for the environment and energy resources. Because of its dilute concentration, very large air volume, and variable flow rate, VAM cannot be burned using traditional combustion devices except as combustible air, and solving this near-limit combustion problem is still a great challenge.

After decades of continuous efforts, great progress has been made in this field. Currently, the main processing technologies include thermal or catalytic reverse flow reactors (RFRs)—a kind of reactor relying on flow reversal after a period repeatedly for autothermal operation, recuperative gas turbines, and catalytic monolith reactors.4 Among these technologies, the RFR is considered to be one of the most promising because of its superiority in dealing with dilute fuel gas with a high flow rate below the lean flammability limit in autothermal operation with a relative low cost.

RFRs have been widely investigated for the combustion of methane. We learned that the first RFR system for combustion of a dilute methane/air gas mixture was proposed by Gogin et al. from Gosiewski’s paper5. A series of studies on catalytic RFR (named CH4MIN) applications for the oxidation of lean methane from coal mine emissions was conducted by CanmetENERGY, with a capacity of 900 m3/h, a minimum VAM concentration requirement of 0.15% and a methane removal efficiency of 95%.6 A thermal RFR product with a horizontal single bed structure was produced by the MEGTEC Company, with a capacity of 125 thousand m3/h, a minimum VAM conversion requirement of 0.2% and a methane removal efficiency of 97%.7 In addition, VAM combustion research has been undertaken by Gosiewski and Pawlaczuk et al. since 2001, with a catalytic RFR and a thermal RFR produced by them.8
Compared to a catalytic RFR9–13 (with the use of a catalyst in addition to inert ceramics), a thermal RFR is a better and less expensive solution when the VAM concentration is high,14 and this RFR has been more commonly used.15–17

Even though many projects on thermal RFRs for VAM or dilute methane have been carried out,18 much progress remains to be made in terms of the theory of thermal RFRs for methane. In addition, previous studies are mainly focused on the operating temperature profile, autothermal concentration, dilute methane combustion mechanism, and so on.

In the view of the thermal RFR operating temperature profile and autothermal operation, Gosiewski and Pawlaczyk19 estimated that a thermal RFR for methane combustion requires an adiabatic temperature increase of ~265 °C per 1 CH4 vol %, which means that VAM combustion in a thermal RFR should be autothermal for CH4 concentrations above ~0.19 vol %, with the maximum temperature below 1100 °C. Lan and Li20 concluded that the minimum concentration of methane in a thermal RFR would be as low as 0.18% with a maximum temperature of over 1127 °C based on three-dimensional numerical investigation and analyzed the effect of the homogeneous flow channel length on the thermal combustion of dilute methane.

In a study of the dilute methane thermal oxidation reaction mechanism, Wang et al.21 developed a reduced two-step mechanism to describe methane combustion in a monolith packed reactor and an empty reactor based on a homogeneous combustion experimental investigation of dilute methane/air mixtures in reactors packed with and without a monolith. Slepterev et al.22 carried out experiments on the homogeneous deep oxidation reaction mechanism of lean methane mixtures in fixed beds of ceramic spheres, considered that the methane oxidation occurs via a consecutive scheme of CO formation, found that CO oxidation is visibly inhibited by methane, and presented recommended kinetic equations and parameters. Extensive research has shown that the selectivity of methane oxidation to CO reaches 70–90%, passing through a maximum with increasing temperature, while the degree of methane conversion depends on the reactor packing and diameter.23 Pawlaczyk and Gosiewski24 studied the kinetics of dilute methane thermal combustion in monolith materials and put forward a method for calculating the reaction rate combining low-temperature kinetic parameters and high-temperature kinetic parameters for further simulation studies. In addition, Pawlaczyk and Gosiewski25 concluded that the combustion mechanism in monolith layers includes a combination of heterogeneous surface combustion and homogeneous combustion in the gas phase through experimental research, and the contributions of the two mechanisms depend on the temperature.

To date, no detailed mechanisms, nor skeletal/reduced mechanisms, for ultra-lean mixtures under ambient pressure conditions have been well established.7 The studies on the kinetics of dilute methane in honeycomb ceramics under ambient pressure conditions are insufficient, and the correction and accuracy of the previous RFR simulation results based on immature mechanisms do not provide satisfactory guidance for the optimization design of lab-scale, much less industrial-scale, thermal RFRs, especially under the condition of heat recovery by extracting heat from the RFR. Additionally, systematic experiments of a bench-scale thermal RFR to analyze the effect of single factors, such as the VAM concentration and flow rate, on the RFR temperature, methane conversion, and system stability have not been thoroughly investigated.

In this paper, an experimental thermal RFR system is designed for verification of the thermal oxidation of VAM, with heat recovery (through a hot water medium) realized by extracting hot flue gas from the RFR. The impacts of single operating parameters (inlet VAM concentration, switching time, flow rate, and so forth.) on the methane conversion and temperature profile during the entire process are analyzed to reveal the combustion characteristics of the thermal RFR, and some valuable conclusions are provided.

2. EXPERIMENTAL SECTION

2.1. Experimental System. An experimental device was constructed to test the VAM thermal oxidation performance under different operating conditions, as shown in Figure 1. The main structure of the RFR is divided into inert ceramic layers I, the combustion room, and inert ceramic layers II. In addition, the power of the electric heating elements arranged in the combustion room is 20 kW, with the purpose of preheating
ceramic layers I and the combustion room in the start-up period of the RFR.

Each cycle of thermal oxidation of VAM in the RFR involves two reverse half cycles: the first half cycle flow direction is ceramic layers I → combustion room → ceramic layers II, and the second half cycle flow direction is reversed. During the first half cycle, switching valve I is in the state of the ceramic layer being connected to the VAM flow and switching valve II is in the state of the outlet being opened to the stack. Thus, the VAM mixture flows through the RFR from the left to ceramic layers I, is heated to over the methane ignition temperature, and is then oxidized in the combustion room. The combustible gas continues to flow through ceramic layers II, extracts heat energy from the ceramics, leaves the RFR and enters the stack, passing through switching valve II.

In the reverse flow half cycle, the flow direction of the VAM in the RFR is reversed by flipping switching valve I and switching valve II. The VAM mixture flows through the RFR from the bottom right of ceramic layers II, is heated to over the methane ignition temperature in ceramic layers II, is oxidized in the combustion room, and is transported to heat ceramic layers I in the form of combustion flue gas.

The shell of the RFR is made of carbon steel to allow operation beyond the temperature of 800 °C, with an actual operating temperature of 30–100 °C during the experimental process. The thickness of the RFR steel wall is 0.01 m, with a density of 7.85 × 10^3 kg/m^3, a specific heat capacity of 460 J/kg/°C, and a thermal conductivity of 13.6 W/m/°C. A thermal insulation layer with a thickness of 0.2 m, arranged between the shell and the ceramics to reduce the heat loss of the RFR, is also fixed between the steel shell and the combustion room of the RFR. The thickness of the insulations is 0.2 m, with a density of 130 kg/m^3 and a specific heat capacity of 1010 J/kg/°C.

The main characteristics of the honeycomb ceramics are as follows: total size, 0.3 × 0.3 × 0.1 m; pore fraction, 56.25%; specific surface area, 750 m^2/m^3; pore size, 0.003 × 0.003 m; channel wall thickness, 0.001 m; packing density, 0.85 × 10^3 kg/m^3; density, 2.5 × 10^3 kg/m^3; specific heat capacity, 850–1100 J/kg/°C; thermal conductivity, 1.5–2.3 W/m/°C; and maximum allowable temperature for long periods, less than 1200 °C. The commercial honeycomb ceramics used in the experiments are composed of cordierite, with a cuboid shape.

Before operation, the inert ceramic beds are preheated to a certain temperature above the methane ignition temperature by two sets of electric heating elements fixed on the middle wall of the combustion room.

Two thermocouples are used to measure the temperature of the mixture gas at the inlet and outlet of the RFR. A total of four thermocouples are placed in different layers of the inert ceramics near the thermal insulation wall to obtain the temperature profiles of the preheated section. A total of three thermocouples are used to measure the temperature of the combustion room of the RFR. Meanwhile, two thermocouples are distributed in the inlet and outlet pipeline of the water loop of the heat exchanger. For more accurate experimental results, the concentrations of CH₄ and NOₓ after combustion in the RFR outlet are detected by gas chromatography.

The variation in the methane content in the gas composition from the inlet to the outlet of the RFR, the period that single direction flow lasts, flow rate of VAM gas, and the flow rate of VAM gas that directly discharges without oxidation are used to determine the efficiency of thermal oxidation according to eqs 1 and 2, while eq 1 stands for average methane conversion considering the influence of switching valve open/close action.

\[
\eta_{CH_4} = \left(1 - \frac{C_{CH_4, out}}{C_{CH_4, in}} \right) \times 100\%
\]

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\]

2.2. Experimental Conditions. Switching valves I and II, which control the RFR flow directions, are dominated by time relays with a fixed time. The thermocouples used in the experiments for measuring the temperature are K-type, with a precision of 0.5% over the entire temperature range studied. The VAM is simulated by a mixture of domestic gas and ambient air. The mixture is prepared by controlling the methane concentration of the mixture at the inlet of the RFR. During the experimental processes, some gas composition samples at the inlet and outlet of the RFR will be taken by the gas sample bags for component analysis to calculate the methane conversion.

To guarantee the precision of the mixture, with the aim of simulating VAM using domestic gas and ambient air, a special static mixer was designed, and the pipe diameter for supplying the mixture gas was selected as 0.2 m, with a pipe length of over 10 m after the mixer. Before the actual thermal state experiment, the methane concentration uniformity of the inlet VAM flow in the delivery pipe was tested by a portable methane concentration detector. A pipe opening was made at a distance from the mixer close to the inlet of the RFR, and the probe of the detector was radially inserted into the pipe from the opening to test the methane concentration at different points of the same cross section of the VAM delivery pipe.

3. RESULTS AND DISCUSSION

A series of experiments for evaluating the VAM thermal oxidation characteristics in the bench-scale thermal RFR were carried out, including experiments on the system start-up process and the effects of the switching time, inlet VAM, flow rate, and heat extraction on thermal oxidation in the RFR.

To conveniently describe the temperature profile of the RFR by thermocouples from different heights in the ceramic layers and thermocouples horizontally arranged in the combustion room in two-dimensional figures, the vertical ceramic layers are unfolded in the horizontal direction, and the left and right sides of the ceramic layers are placed at each end of the combustion room. The total length of the RFR is easily determined to be 5.2 m, as shown in Figure 2.

The experimental conditions and results are shown in Table 1 and Figure 3. In general, methane conversion exceeding 96%
can be observed. The main idea for investigating thermal oxidation is to survey the temperature profile in the RFR, methane conversion, and NO\textsubscript{x} emissions during the experiment.

3.1. System Start-Up Characteristics. In addition to the experiments listed in Table 1, we also carried out experiments to study the start-up characteristics of the thermal RFR for dealing with VAM via thermal oxidation.

First, the honeycomb ceramic layers are heated through electric heating elements. With the help of VAM flow switching, after approximately 6 h of electric heating, the temperature in the combustion room exceeds 700 °C, and the temperature in the upper layer of the honeycomb ceramics is over 600 °C.

Second, the simulated VAM gas (the inlet methane concentration \(C_{\text{CH}_4,\text{in}}\) is 0.35%, and the flow rate is 500 Nm\(^3\)/h) flows into the RFR, transfers some of the heat in ceramic layers I to ceramic layers II through the VAM flow, preheated, and combusted in the RFR. The methane concentration at the outlet of the RFR in several initial reverse flow cycles of this step can be seen in Figure 4. The methane conversion \(\eta'_{\text{CH}_4}\) is strongly related to the temperature profile in the honeycomb ceramic layers. \(\eta'_{\text{CH}_4}\) changes rapidly in the initial cycles. Each half cycle time \(t_c\) is 90 s. As the RFR runs continuously, the entire temperature in the RFR gradually increases under the two reverse flow directions. Finally, the system reaches the autothermal state under this condition. In subsequent cycles, flow reversal begins to repeat the previous behavior, called the cyclic steady state (CSS). In addition, the system reaches a high methane conversion \(\eta'_{\text{CH}_4}\) (above 96%) after 90 min of the reverse flow process. No NO\textsubscript{x} is found in the gas samples at the outlet of the RFR to the stack, with the highest temperature in the RFR of 728 °C.

3.2. Effect of the Switching Time. Given a constant flow rate and inlet VAM concentration, experiments to investigate the effect of the switching time were carried out. The switching time \(T_{\text{switch}}\) can be evaluated by the following equation\(^26\)

\[
T_{\text{switch}} = \frac{L_{\text{act}}}{v_{\text{hf}}}
\]

where \(L_{\text{act}}\) is obtained using eqs 4–6, and \(v_{\text{hf}}\) is obtained using eq 7

\[
L_{\text{hf}} = L - 2(T_{\text{act}} - T_0) \frac{dx}{dT}
\]

Table 1. Experimental Conditions

| item             | unit | value       |
|------------------|------|-------------|
| VAM concentration |      | 0.20–0.99%  |
| half cycle time  | s    | 60–120      |
| flow rate (m\(^3\)/h) | Nm\(^3\)/h | 500–1000    |

The temperature profiles in the CSS at the end of the start-up process in the forward half cycles are shown in Figure 4. The temperatures of the top layers of the ceramics and the combustion room are above 600 °C, higher than the methane ignition temperature of 538 °C. The temperature profiles in the CSS do not appear to be unique because of slight fluctuations in the inlet VAM concentration and the flow rate. Different inlet VAM concentrations would have different temperature profiles to meet different heat storage needs, which will be analyzed in the next section.

![Figure 3. Experimental results under different conditions (inlet VAM concentration, switching time, flow rate, and so forth.).](Image)

![Figure 4. Temperature profile in the CSS for forward half cycles. (A) 3D visualization of the temperature profile. (B) 2D contour figure of the temperature profile.](Image)
The value of the switching time is easily obtained from eqs 3–7 through mathematical calculation and is approximately 268–921 s at the inlet VAM concentration of 0.3–1.0%. To be conservative, we adopted a smaller switching time range during experiments, from 60 to 120 s, to avoid combustion reaction extinction.

Figure 5 shows the temperature profile in the CSS for different switching times (called the half cycle time, in which two switching times are needed for a whole cycle) at the inlet VAM concentration of 0.46% and a flow rate of 800 Nm$^3$/h. As the switching time increases, the temperature profile of ceramic layers I and II exhibits a downtrend, and the peak temperature of the RFR decreases. The high temperature zone becomes wider, as shown in Figure 7. The temperature of the RFR becomes higher, and the high temperature zone shifts toward the outlet side, and the exhaust temperature increases slightly.

We can determine that the methane conversion is related to the temperature of the combustion room. When the temperature of the combustion room is above 700 °C, the methane can be almost totally converted to CO$_2$ and H$_2$O.

According to the experimental data of the inlet VAM concentration and outlet VAM concentration under different switching time conditions of 60, 90, and 120 s, we can obtain the methane conversions $\eta'_{\text{CH}_4}$ through eq 2.

Additionally, we can obtain the average methane conversion $\eta_{\text{CH}_4}$ as shown in Figure 6, through eq 1 after calculating the pure methane volume that rushes out when the switching control valve is opened or closed over 1 h, as the volume rushing out can be estimated by the parameters in Section 2.1. Little difference is found between methane conversion $\eta_{\text{CH}_4}$ for the switching times of 60, 90, and 120 s, with the same trend observed for $\eta'_{\text{CH}_4}$. The switching time clearly has a significant influence on the methane conversion in terms of lowering the average methane conversion $\eta_{\text{CH}_4}$, even though little difference is found between the $\eta_{\text{CH}_4}$ values for different switching times.

No NO$_x$ was detected in the gas samples at the outlet of the RFR to the stack, and the highest temperature in the RFR was 810 °C at the time the gas samples were taken for measurement.

### 3.3. Effect of the Inlet VAM Concentration

Given a constant flow rate and switching time, experiments to determine the effect of the inlet VAM concentration were performed, with the inlet VAM concentration ranging from 0.20 to 0.99%. As the inlet VAM concentration increases, the peak temperature of the RFR becomes higher, and the high temperature zone becomes wider, as shown in Figure 7. The main reason for this phenomenon is that a higher methane concentration in VAM could result in more heat release from combustion. The peak temperature of the RFR can reach 800 °C when the inlet VAM concentration is above 0.6%, while this temperature drops to 700 °C when the inlet VAM concentration is as low as 0.3%. The extracted portion of hot flue gas can be used for producing hot water using a heat exchanger.

When the inlet VAM concentration is 0.2%, the heat extracted from the VAM combustion cannot maintain the autothermal operation of the system (mainly counteracting the outlet flue gas heat loss and surface heat dissipation), which would lead to gradual combustion reaction extinction in the RFR. The temperature profile for 0.2% concentration in Figure 7 actually has a downtrend that leads to combustion reaction extinction.
extinction in the RFR. For the purpose of CSS comparison, the downtrend of the 0.2% temperature profile is not shown in Figure 7.

The inlet VAM concentration will not be suitable when it is set too high, as the heat release rate will be much greater than the gas flow rate, which would cause damage because of an explosion. From eq 6, we can determine that the adiabatic temperature rise of the inlet VAM is 280.5 °C for a methane concentration of 1.0%. The temperatures of the ceramic top layers are commonly above 650 °C, and the temperature in the combustion room can easily reach 900 °C if there is little flue extraction from the RFR. Therefore, the inlet VAM concentration is usually maintained below 1% for temperature control and safety purposes.

We learned from experiments that the RFR will be in autothermal operation in the CSS above the VAM concentration of 0.30%; additionally, the outlet methane concentration will remain low and decrease when the inlet VAM concentration slightly increases. Because all of the methane conversion values are approximately 96%, we can assume that no clear differences exist between the methane conversion values $\eta'_{CH4}$ for different inlet VAM concentrations when the RFR is operating at a VAM concentration above 0.3%, as shown in Figure 8.

No NOx was found in the gas samples at the outlet of the RFR when evaluating the methane conversion, with the highest temperature in the RFR of 850 °C.

3.4. Effect of the Flow Rate. Given a constant switching time and inlet VAM concentration, experiments to study the effect of the flow rate were performed, with the flow rate fluctuating from 500 to 1000 Nm³/h.

We carried out experiments under the conditions of a VAM concentration of 0.75% and a switching time of 120 s. We found that the peak temperature of the RFR rises as the flow rate increases, similar to the effect of the inlet VAM concentration on the RFR. When the RFR reaches the CSS, the temperature profile has a tendency to move toward the outlet side as the flow rate increases, as shown in Figure 9.

In a forward half cycle, the temperature profile of the RFR gradually moves toward the outlet side with increasing switching time, as shown in Figure 10. We conclude that the distance that the heat wave moves in the ceramic layers is approximately 0.5 m from the position at the half cycle start for

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**Figure 7.** Temperature profile in the CSS for different VAM concentrations in a forward half cycle.

**Figure 8.** Methane conversion and outlet methane concentration for different inlet VAM concentrations.

**Figure 9.** Temperature profile in the CSS for different VAM flows in a forward half cycle.

**Figure 10.** Temperature profile in the CSS for different switching times in a forward half cycle.
a switching time of 120 s. This distance can be thought of as the distance over which the same temperature transfers to each side of the ceramic layers.

Even though the methane conversion fluctuates as the flow rate ranges from 500 to 1000 Nm³/h, it still remains above 95%, and no clear trend is observed in the methane conversion fluctuation as the flow rate increases, which means that the flow rate has little influence on the methane conversion $\eta'_{CH_4}$ as shown in Figure 11. However, we can see that average methane conversion $\eta_{CH_4}$ for a flow of 500 Nm³/h is obviously lower by more than 1% compared to the other flow rates. A low flow rate appears to have some influence on the average methane conversion $\eta_{CH_4}$. In addition, no NO$_x$ is found during this experiment, with the highest temperature in the RFR of 830 °C.

3.5. Effect of Heat Extraction. Given a constant flow rate and switching time, experiments to survey the effect of heat extraction under different inlet VAM concentrations were implemented as follows.

The principle of choosing the extraction flow rate of flue gas is based on the autothermal operation of the RFR in the CSS. In addition, the peak temperature in the RFR will clearly rise if less high-temperature flue gas is extracted.

When the RFR operates at a relatively high VAM concentration, such as 0.75%, the combustion of methane could be in the autothermal mode in the CSS of the RFR, and heat could be exported outside by flue gas extraction at the same time, with the purpose of avoiding overheating of the ceramic layers. The heat extraction experimental conditions were as follows: flow rate, 800 Nm³/h; switching time, 90 s; VAM concentrations, 0.20, 0.30, 0.46, 0.60, 0.75, and 0.99%; and water flow rate of the water-flue gas exchanger, 2.7 t/h.

The experimental result is shown in Figure 12. When the VAM concentration is 0.99%, the flue temperature is 900 °C, the flue flow is 212 Nm³/h, and the water temperature will be able to rise 21.06 °C, as measured by thermocouples in the water pipes. The flue temperature represents the peak temperature of the RFR as the VAM concentration changes. In addition, no NO$_x$ is found during this experiment.

![Figure 11. Methane conversion in the CSS for different flow rates.](image)

![Figure 12. Heat extraction for different VAM concentrations.](image)

4. CONCLUSIONS

(1) An appropriate switching time is good for the stability of RFR operation, especially at low inlet VAM concentrations, and a switching time of 90–120 s is suitable as the half cycle time according to experiments.

(2) The thermal RFR system can operate over a wide range of inlet VAM concentrations with autothermal operation, and the RFR can reach the CSS at a concentration as low as 0.30%. The high temperature zone of the RFR becomes wider as the inlet VAM concentration increases, which will be beneficial for the CSS. Even though the outlet methane concentration decreases as the inlet VAM concentration increases, no clear difference is observed between the methane conversion values as the VAM concentration ranges from 0.3 to 0.99%, which means that the VAM concentration has a slight influence on the methane conversion $\eta_{CH_4'}$ in the CSS.

(3) The peak temperature of the RFR rises as the flow rate increases in the CSS, and the temperature profile has a tendency to move toward the outlet side at the same time. No NO$_x$ is found in the outlet of the RFR to the stack during the experiments with a maximum temperature in the RFR of 850 °C. Temperature profile control of the thermal RFR would be fundamental to thermal oxidation and reduction of NO$_x$, and a more effective control strategy would be essential for an industrial-scale RFR. A low flow rate has some influence on the average methane conversion, and this phenomenon needs to be considered when running an industrial-scale thermal RFR.

(4) The RFR can export heat outside through flue gas extraction when the RFR operates under a relatively high VAM concentration in the CSS for the purpose of autothermal operation and thermal utilization. The higher the VAM concentration is, the higher the hot water temperature rise through the exchanger outside the RFR.

(5) We determine that the RFR can run at concentrations above 0.30% in the CSS and have heat remaining for utilization in the form of high temperature flue gas. A proper switching time, peak temperature, and optimized length of the high temperature zone need to be selected for stable operation.
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NOMENCLATURE

$C_{CH_4 \text{out}}$ average methane concentration at the RFR outlet, v/v %
$C_{CH_4 \text{in}}$ average methane concentration at the RFR inlet, v/v %
$F_m$ flow rate of VAM, m$^3$/h
$F_{\text{rushed}}$ flow rate of the VAM gas that rushed to the stack without combustion as the switching valve changes the flow direction, m$^3$/h
$t_{\text{tot}}$ total evaluated time, s
$t_{\text{switch}}$ the period that single direction flow lasts, s
$L_{\text{hf}}$ distance of the heat front moving distance on either side of the ceramic layers, m
$L$ length of either side of the ceramic layers, m
$T_{\text{ini}}$ initial temperature of methane oxidation, °C
$T_0$ inlet temperature, °C
$k_{g-s}$ gas–solid heat transfer coefficient, W/m$^2$/°C
$c_{\text{pg}}$ gas-phase heat capacity, J/kg/°C
$k_{\text{eff}}$ effective axial thermal conductivity, W/m/°C
$\Delta T_{\text{ad}}$ adiabatic temperature rise, °C
$\Delta H$ enthalpy of combustion, J/mol
$c_0$ inlet volume molar concentration, mol/m$^3$
$c_{\text{pg},0}$ inlet gas specific heat capacity, J/kg/°C
$\frac{dT}{dx}$ temperature gradient, °C/m
$v_{\text{hf}}$ heat front moving velocity, m/s
$u_0$ inlet superficial velocity of gas, m/s

GREEK SYMBOLS

$\eta_{\text{CH}_4}$ average conversion efficiency of methane, %; $\eta_{\text{CH}_4,1}$ conversion efficiency of methane during a half cycle time ignoring the influence of the switching flow direction, v/v%; $\varepsilon$ porosity of ceramic layers; $a_{\phi}$ specific surface area, m$^2$/m$^3$; $\rho_{\text{g},0}$ inlet gas-phase density, kg/m$^3$

SUBSCRIPTS AND SUPERSCRIPTS

out, at the outlet; av, average; in, at the inlet; rush, expel VAM to the stack without combustion; switch, half cycle period; hf, heat front; ini, initial; 0, inlet; g, gas; solid; g, gas; eff, effective; adia, adiabatic

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