Heat Recirculation Effect on the Structure of Wood Dust Flame Propagation

M. Bidabadi, M. J. Noroozi, J. Fereidooni*

Combustion Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology

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A B S T R A C T

A model for heat-recirculating micro combustor is developed. It investigates the structure of laminar, one-dimensional and steady state flame propagation in uniformly premixed wood particles with considering the effects of heat recirculation caused by configuration of micro combustor. The flame structure is divided into three regions: a preheat-devolatilization zone where the rate of the gas-phase chemical reaction is small; a narrow reaction zone where convection and the rate of devolatilization of the fuel particles are small; and finally a convection zone where diffusive terms in the conservation equation are small. In this model, it is assumed that the fuel particles vaporize first to yield a gaseous fuel of known chemical structure. The analysis is investigated in the asymptotic limit. The overall investigation of this study leads to a novel non-linear burning velocity correlation that heat recirculation term is considered to calculate it. The results shows that heat recirculation affect the flame structure by different parameters. Burning velocity and flame temperature are the most important of these parameters. Furthermore, as the equivalence ratio increases and the wood particle size decreases, the combustion process in micro combustor can be more stable.


Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>parameter characterizing rate of devolatilization of fuel particles [kg/(m²·K·s)]</td>
</tr>
<tr>
<td>B</td>
<td>frequency factor characterizing rate of gas phase oxidation of the gaseous fuel</td>
</tr>
<tr>
<td>C</td>
<td>specific heat capacity of mixture [J/(kg·K)]</td>
</tr>
<tr>
<td>C_p</td>
<td>specific heat capacity of the gas [J/(kg·K)]</td>
</tr>
<tr>
<td>C_S</td>
<td>specific heat capacity of a fuel particle [J/(kg·K)]</td>
</tr>
<tr>
<td>D</td>
<td>molecular diffusion coefficient</td>
</tr>
<tr>
<td>d</td>
<td>diameter of micro combustor [m]</td>
</tr>
<tr>
<td>E</td>
<td>activation energy characterizing the gas phase reaction [J/mol]</td>
</tr>
<tr>
<td>h_nu</td>
<td>convective heat transfer coefficient between the combustion flow and wall [W/(m²·K)]</td>
</tr>
<tr>
<td>k</td>
<td>rate constant of the gas-phase reaction</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>n</td>
<td>temperature exponent characterizing rate of devolatilization of fuel particles</td>
</tr>
<tr>
<td>n_s</td>
<td>local number density of particles (number of particles per unit volume) [1/m³]</td>
</tr>
<tr>
<td>P_e</td>
<td>Peclet number</td>
</tr>
<tr>
<td>Q</td>
<td>heat release per unit mass of gaseous fuel consumed [J/kg]</td>
</tr>
<tr>
<td>Q_h</td>
<td>heat associated with devolatilization unit mass of fuel [J/kg]</td>
</tr>
<tr>
<td>R</td>
<td>universal gas constant [J/(mol·K)]</td>
</tr>
<tr>
<td>r</td>
<td>radius of fuel particle [m]</td>
</tr>
<tr>
<td>T</td>
<td>temperature [K]</td>
</tr>
<tr>
<td>v</td>
<td>velocity [m/s]</td>
</tr>
<tr>
<td>v_w</td>
<td>burning velocity calculated including heat of devolatilization of fuel particles [m/s]</td>
</tr>
<tr>
<td>W_r</td>
<td>molecular weight of gaseous fuel [kg/mol]</td>
</tr>
<tr>
<td>w_r</td>
<td>reaction rate characterizing consumption of gaseous fuel [kg/(m³·s)]</td>
</tr>
<tr>
<td>w_v</td>
<td>rate of devolatilization of fuel particles [kg/(m³·s)]</td>
</tr>
<tr>
<td>x'</td>
<td>spatial coordinate [m]</td>
</tr>
<tr>
<td>Y</td>
<td>mass fraction</td>
</tr>
<tr>
<td>Z_e</td>
<td>Zeldovich number</td>
</tr>
<tr>
<td>z</td>
<td>scaled independent variable</td>
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Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>\rho</td>
<td>value of \theta calculated neglecting heat of devolatilization of particles</td>
</tr>
<tr>
<td>\lambda</td>
<td>thermal conductivity [W/(m·K)]</td>
</tr>
<tr>
<td>\rho</td>
<td>density of the reactant mixture [kg/m³]</td>
</tr>
<tr>
<td>\phi_e</td>
<td>equivalence ratio based on fuel available in the particles in the ambient reactant stream</td>
</tr>
<tr>
<td>v</td>
<td>stoichiometric coefficient</td>
</tr>
</tbody>
</table>

Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>F</td>
<td>gaseous fuel</td>
</tr>
<tr>
<td>f</td>
<td>conditions at the reaction zone</td>
</tr>
<tr>
<td>s</td>
<td>fuel particles</td>
</tr>
<tr>
<td>u</td>
<td>conditions in the ambient reactant stream</td>
</tr>
<tr>
<td>w</td>
<td>wall</td>
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*Corresponding author: Email: fereidooni@iust.ac.ir
1. INTRODUCTION

A sudden rise in using micro-electromechanical-systems (MEMS) encouraged the development of power sources that have higher power density and smaller volume. Vital usages of these power sources are micro gas turbines [1], the micro thermoelectric device [2], the micro thermo-photovoltaic (TPV) system [3], producing propulsive force in pico- and nano-satellites [4], have spurred the investigators to supersede these systems for common electrochemical batteries. The way of electrical power generation from combustion in micro electromechanical systems is such that the heat or radiation which arise from the combustion is converted to electrical energy by thermoelectric or thermo photovoltaic elements.

Hydrocarbon fuels in comparison with lithium-ion batteries (as one of the sources of micro power generation) contain about 100 times more energy per unit mass. Thus, the systems that convert fuel to electrical energy, with the efficiency of more than one percent energy conversion from chemical energy to electrical energy, is better than prevalent electric batteries. In small sizes, heat loss and friction become important and effective phenomena. Hence, design of systems with extremely small sizes, on the basis of systems with common sizes, like internal combustion engines is not possible. So, in these systems, heat recirculation should be used by which transferring heat from combustion products to reactants, the whole enthalpy of reactants (adding heat and chemical enthalpies) is more than the enthalpy of cold reactants. Therefore, combustion can be sustained by heat recirculation under some conditions such as lean mixtures, small heating value fuels, large heat losses and etc that result extinguishment [5].

Finite sources of fossil fuel and resultant pollution from combustion of these valuable sources was a stimulus for experts who work in energy section of developed countries to replace these sources with renewable energy sources. These new sources of energy are which are compatible with environment. One of the biggest non fossil sources is biomass which from the beginning of the existence of human has played a significant role in its life.

Since biomass usually exists in the solid phase and comes from nature, it is found in different figures and sizes. Thus, it causes a challenge in replacing these sources by fossil sources. One way to solve this problem is breaking it into extremely small sizes and dispersing them in air, in a way that it forms a solid particle-cloud. In such a way, it comes near to a gas mixture of fuel and oxidizer. In these conditions, flame propagation through this particle-cloud is comparable with the flame propagation through a premixed gas reactant.

In previous works, Daou and Matalon [6, 7] described the effects of heat loss on the structure of premixed flames propagating in channels which the wall of channels were constant-temperature. Chen et al. [5] presented a model that is used a perfectly stirred reactor to study non-adiabatic combustion in heat-recirculating combustors in which heat from the post-flame is transferred upstream. This work showed that in microscale, the stream-wise heat conduction is dominant. Leach et al. [8] described the similar effects in micro-channels. They have been showed that for determining the performance of micro combustor, axial conduction of heat through the walls has an important effect [9]. Bidabadi et al. [10] investigated the role of heat recirculation and non-unity Lewis number on the combustion of organic dust particles. They defined a heat recirculation coefficient and observed that the increase in this coefficient leads to increase the burning velocity and flame temperature.

In this work, the structure of wood dust flame has been studied. The role of heat recirculation has been investigated in order to estimate the change of flame characteristic as burning velocity and flame temperature. The difference between this research and similar works is such that here wood particle-cloud is used as the fuel in a cylindrical micro combustor. Additionally, the effects of heat recirculated and heat loss are studied.

2. APPROACH

As Figure 1 shows, the structure of flame propagation is containing of three zones based on large zelovich number, and high reaction rate which results in thin reaction zone. In the preheat-devolatilization zone ($\infty < x < 0$), particles heat up to reach the pyrolysis temperature. In this zone, chemical reaction between the gaseous fuel and oxidizer is neglected. The next zone is reaction zone in which particles are oxidized, and burnt. In this zone ($0 < x < 0^3$), the convective terms and pyrolysis terms in the conservation equations are presumed to be small in comparison with the reaction term. Another zone is post flame zone ($0^+ < x < \infty$) in which the diffuse terms in the conservation equations are assumed to be small in comparison with others.

![Figure 1. The structure of flame propagation and heat recirculation](image)
The equation of state is:
\[ \rho T = \text{Const.} \] (8)

The heat capacity in Equation (5) is the sum of heat capacity of the gas \( C_p \), and heat capacity of the particles \( C_s \), and can be calculated from the following equation:
\[ C = C_s + \frac{4\pi r^3 \rho_s n_s}{3\rho} \] (9)

3. GOVERNING EQUATIONS

Much research has been devoted to the theoretical analysis, computational modeling and experimental studies of combustion [11-13]. Wood particles are devolatilized, and the pyrolysis product is assumed to be a known gaseous compound and this compound then oxidized in reaction zone. Many researches focused on the pyrolysis of biomass particles [14,15]. The devolatilization kinetic is assumed to be represented by the following equation [16].

\[ w = 4A\pi r^2 n_j (T - T_\infty)^\gamma \] (1)

The constant rate of the overall reaction is written in the arhenius form \( K = B\exp(-E/(RT)) \). Also the Zeldovich number, which is presumed to be large, is defined as:
\[ Z_s = \frac{E(T_s - T)}{RT_s^2} \] (2)

The mass conservation law is:
\[ \rho v = \text{Const.} \] (3)

As the thermal conductivity \( \lambda \) is proportional to \( T \), and the diffusion coefficient \( D \) is proportional to \( T^2 \), the governing equations in this problem are nonlinear which can be transformed into a linear form by introducing an independent variable \( x \) that is related to the spatial coordinate \( x' \) as:
\[ x = \int_0^\rho \frac{dx'}{\rho_x} \] (4)

For the combustion of wood particles, the energy equation is derived as:
\[ \rho v C \frac{dT}{dx} = \lambda \left( \frac{d^2T}{dx^2} + \frac{w_j}{\rho} \frac{\rho_c}{\rho} Q - \frac{w_i}{\rho} \frac{\rho_c}{\rho} + \frac{4h_0}{d} (T - T_\infty) \right) \] (5)

The equation of gaseous fuel conservation is:
\[ \rho v \frac{dY_j}{dx} = \rho_j D_j \frac{d^2Y_j}{dx^2} + \frac{w_j}{\rho} \frac{\rho_c}{\rho} Q - \frac{w_j}{\rho} \frac{\rho_c}{\rho} \] (6)

The equation governing the mass fraction of the particles neglecting diffusion can be written as:
\[ \rho v \frac{dY_s}{dx} = -w_i \frac{\rho_i}{\rho} \] (7)
\[ \frac{dy}{dz} = -\gamma y^2_y (\theta^\prime)^2 \]  

(18)

In order to obtain the solution of these differential equations, the asymptotic approach is utilized based on the thin reaction zone.

### Preheat-devolatilization zone \((-\infty < x < 0^-\))

The \(Z_e\), based on the gas-phase oxidation of the gaseous fuel is considered to be large, so chemical reaction between the gaseous fuel and oxidizer is neglected. Consider \(K = 4\text{NaPe}^3/\text{D}\), dimensionless temperature equation and the required boundary condition in the preheat zone according to the above assumptions are extracted as:

\[ \frac{d\theta'}{dz} - K \theta' = 0 \quad \text{for} \quad z = 0 \rightarrow \theta' = 1, \quad z = -\infty \rightarrow \theta' = 0 \]

The above simplified differential equation is solved as:

\[ \theta' = \exp(k'z) \]

where,

\[ k' = \frac{1+\sqrt{1+4K}}{2} \]

In order to determine the mass fraction of the wood particles, the obtained dimensionless temperature correlation is substituted into the Equation (18). Thus Equation (18) and its boundary condition are rewritten as:

\[ \frac{dy_y}{dz} = -\gamma y^2_y \exp(\eta k'z), \quad \text{for} \quad z = -\infty \rightarrow y_y = \frac{Y_{ea}}{Y_{fc}} = \alpha \]

Thus, the correlation for mass fraction of wood particles is followed by:

\[ y_y = \left[ \frac{1}{\alpha} - \alpha \exp(\eta k'z) \right]^{-\eta} \]

where,

\[ \alpha = \frac{\gamma}{3nk'} \]

Replacing the above achieved correlations, for the dimensionless temperature, and wood mass fraction into the gaseous fuel mass fraction yields to:

\[ \frac{dy_y}{dz} = \frac{d^2y_y}{dz^2} + \gamma \left[ \frac{1}{\alpha} - \alpha \exp(\eta k'z) \right] \exp(\eta k'z) \]

(25)

### Post flame zone \((0^+ < x < +\infty)\)

Before we verify the reaction zone, we analyze the post flame zone because we need the matching conditions between the reaction zone and the post flame zone.

In post flame zone, the diffusive terms in the conservation equations are assumed to be small in comparison with other terms, thus the basic Equations (16-18) are obtained as:

\[ \frac{d\theta'}{dz} = -K \theta' \Rightarrow \left[ \frac{dy_y}{dz} \right]_{0^+} = -K \]

\[ \frac{dy_y}{dz} = 0 \Rightarrow \left[ \frac{dy_y}{dz} \right]_{0^+} = 0 \]

\[ \frac{dy_y}{dz} = 0 \rightarrow y_y = cte \]

### Reaction zone \((0^- < x < 0^+)\)

In this zone, the convective terms and devolatilization terms in the conservation equations are presumed to be small in comparison with the diffusive terms and reactive terms. Thus, the governing equations are as follows:

\[ \frac{d^2\theta'}{dz^2} = \frac{\rho_c}{\rho} \]

\[ \frac{d^2y_y}{dz^2} = \frac{\rho_c}{\rho} \]

(30)

(31)

\[ \frac{dy_y}{dz} = 0 \rightarrow y_y = cte \]

(32)

The gaseous fuel reaction rate appearing in the governing equation are evaluated as:

\[ w = \nu_s W_f \kappa C_f \]

(33)

For analyzing the structure of this region, the following expansions are introduced.

\[ y_y = \epsilon(b+y), \quad \eta = \frac{z}{\epsilon}, \quad t = \frac{I - \theta'}{\epsilon} \]

(34)

where, \(b=y_{ef}/\epsilon\) and \(\epsilon=1/Z_e\). The quantities \(t\) and \(b\) are assumed to be of order unity. The Equations (30) and (31) are extracted using Equations (15), (33) and (34) as:

\[ \frac{d^2\theta'}{d\eta^2} = \Lambda(b+y)\exp(-t) \]

(35)

\[ \frac{d^2y_y}{d\eta^2} = 0 \]

(36)
where, quantity $A$ assumed to be of order unity defined as:

$$A = \frac{v_y \lambda \beta e^2}{\rho_s v_c C_2} \exp\left(-\frac{E}{RT}\right)$$  (37)

Now the matching conditions with the solution in the preheat zone ($\eta \to -\infty$), and with the post flame zone ($\eta \to +\infty$) are used, to determine the flame characteristics in this zone. Matching with the post flame zone results in:

$$\left[\frac{dF}{d\eta}\right]_{\eta \to +\infty} = \left[\frac{d\theta^*}{dz}\right]_{\eta \to +\infty} = K$$  (38)

$$\left[\frac{dF}{d\eta}\right]_{\eta \to +\infty} = \left[\frac{d\mu^*}{dz}\right]_{\eta \to +\infty} = 0$$  (39)

Matching with the preheat zone:

$$\left[\frac{dF}{d\eta}\right]_{\eta \to \infty} = \left[\frac{d\theta^*}{dz}\right]_{\eta \to \infty} = -k'$$  (40)

Solution of the Equation (35) and using boundary conditions mentioned above result in:

$$2A(b+1) = k'^2$$  (41)

3.2. Burning velocity  Introducing Equation (41) into Equation (37) yields to the burning velocity as:

$$v_z = \frac{2(b+1)w_y \lambda \beta e^2}{k'^2 \rho_s C_2} \exp\left(-\frac{E}{RT}\right)$$  (42)

If $T_f$ and $b$ are known, the above equation can be used to calculate the burning velocity. For sufficiently high values of $T_f$, it is reasonable to set $y_{2f}=0$ which implies that $b=0$. The matching conditions across the reaction zone are used to evaluate another expression for determination of $T_f$:

$$\left[\frac{d\theta^*}{dz}\right]_{\eta} + \left[\frac{d\mu^*}{dz}\right]_{\eta} = \left[\frac{d\theta^*}{dz}\right]_{\eta} + \left[\frac{d\mu^*}{dz}\right]_{\eta}$$  (43)

then,

$$3w_a e^2 - 3a^2 c \alpha^2 + a^2 - k' - K = 0$$  (44)

If the heat of devolatilization is considered, then the equation of burning velocity can be written:

$$v_z = v_w \exp\left(-\frac{qZ_-}{2}\right)$$  (45)

4. RESULTS AND DISCUSSIONS

In this work heat recirculation effect on the flame structure and combustion characteristics of the wood dust in a micro combustor has been investigated. A standard code is used to analyze the combustion model.

The flame temperature as a function of equivalence ratio is compared with the results of Ref. [10], for validation of the model. As seen in Figure 2, a reasonable agreement is obtained.

![Figure 2](image2.png)

**Figure 2.** The variation of flame temperature as a function of equivalence ratio ($r_p=10 \ \mu m, \ K=0.1$)

The variation of the burning velocity as a function of equivalence ratio, for different values of particle radius is plotted in Figure 3. As observed, by increasing the equivalence ratio, the burning velocity increases, and when particle radius increases, the burning velocity goes down. This phenomenon occurs because with an increase in radius of the particle, the ratio of the particle surface to its volume decreases. So, for a given mass of the particles, there is less surface for oxidizer to react with particle. Hence, the time of reaction increases and as a result, burning velocity decreases.

![Figure 3](image3.png)

**Figure 3.** The variation of burning velocity as a function of equivalence ratio for different values of particle radius

Figure 4 illustrates the variation of flame temperature as a function of equivalence ratio, for different values of particle radius. As shown, with an increase in equivalence ratio, the flame temperature increases. Also, at the constant equivalence ratio, a decrease in
particle radius results in increasing the flame temperature. This is to be expected, because for any given equivalence ratio as particle size becomes smaller, both the number of particles and the total particle surface area increase. As perceived in this figure, the flame temperature increases with an increase in equivalence ratio due to the fact that higher equivalence ratio leads to higher heat of reaction. Therefore, the rate of the chemical reaction speeds up, and the flame temperature increases.

The variation of $D\gamma$ in the length of micro combustor is plotted in Figure 6. The Equation (10) justifies the unfamiliar trend of this parameter. The asymptotic line is somewhere that gas temperature reaches to the wall temperature.

The power density of a micro combustor is defined as $\dot{W} = W/V$, where $\dot{W}$ is the power generated by the combustion process and $V$ is the volume of the combustor in which the chemical energy is released.

The variation of power density of the micro combustor as a function of equivalence ratio is plotted in Figure 7. As seen in this figure, by increasing the equivalence ratio, power density of micro combustor also increases. These results may be explained as follows: in Figure 4, we saw that the flame temperature is increased with an increase in equivalence ratio. An increase in the flame temperature is equivalent to an increase in the heat transfer rate and thus power generated by the combustion process also increases. The power density of a micro combustor is in direct proportion to the generated power and so it increases.
Figure 8 shows the variation of the dimensionless mass fraction of gaseous fuel and wood particles in preheat zone. It is evident that a decrease in mass fraction of the particles results in an increase in mass fraction of the gaseous fuel. Indeed, the role of mass diffusion term in the mass conservation equation becomes more prominent with the approaching the flame zone. Therefore, the conversion rate of wood particles to gaseous fuel increases.

As shown in Figure 9, the variation of heat capacity of the gas is small when the variation of equivalence ratio is great. Therefore, its variation is similar to wide range of gases.

![Image](image-url)

**Figure 8.** The variation of the dimensionless mass fraction of gaseous fuel and wood particles in preheat zone

![Image](image-url)

**Figure 9.** The variation of heat capacity of the gas as a function of equivalence ratio

### 5. CONCLUSION

If many combustible dusts dispersed as a cloud in air and ignited, it will allow a flame to propagate through the cloud in a manner similar to the propagation of flames in premixed fuel oxidant gases. The violence of explosion on particle size strongly depends on the interplay of phenomena controlling the combustion/heating of the solid material, such as pyrolysis, gas-phase mixing, gas-phase combustion, and the dispersion of the dust particles in air.

Heat recirculation as an important parameter in the wood dust flame propagation is investigated. In the steady analysis, dust flame is separated to three zones: broad preheat-devolatilization zone, thin reaction zone, and finally the post-flame zone. Heat is circulated form the exhaust flow in post flame zone into the preheat zone.

Result shows that with an increase in the equivalence ratio, the burning velocity, the flame temperature and the power density of micro combustor increase. As it is reported, gas temperature in preheat zone increase when heat recirculation is considered. It means that heat recirculation is a process which results in advantages of high temperature combustion. Moreover, combustion process in micro combustor will remain more stable due to an increase in the equivalence ratio and a decrease in the wood particle size.

### 6. REFERENCES

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Combustion Research Laboratory, School of Mechanical Engineering, Iran University of Science and Technology

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چکیده

مدلی تحلیلی برای یک محضه ی احتراق بسیار کوچک همرا به گردش حرارتی در آن توسعه داده شد. در این مقاله ساختار شعله ای آرام، یک پیشگیری و یک پایان در پیش مرحله همگن از ذرات چوب منتشر می‌گردد، با در نظر گرفتن اثرات گردش حرارتی که از طریق ساختار محضه ای احتراق اعمال می‌گردد. بررسی می‌شود: یک ناحیه ی پیشگیری ویژه که در آن نرخ و آکنش شیمیایی افزایش کرده است، یک ناحیه ی واکنش پیازی که در آن جابجایی و نرخ تبخير ذرات سوخت کوچک سریع می‌باشد، و در آخر یک ناحیه ی جابجایی که در آن جمله‌های مرتب به فنر در معادلات یک کوچک هستند. در این مقاله این گونه‌ای یک ساختار شیمیایی مشخص را می‌بینید. تحلیلی که در این مقاله انجام شده است، به صورت حد جدیدی می‌باشد. بررسی کلی این مطالعه محرک به عبارت نوینی بسیار سرعت سوزش غیر حضی می‌گردد که در آن گردش حرارتی منجر به تبدیل ساختار شعله از یک گردش حرارتی تويل و پاسخگویی به سرعت سوزش شناسی این پایداری بهتری نسبت به ریزتر کردن داده می‌شود. محققین افراق نسبت هم ارزو و برتری کردن درات چوب به بهتر شدن و پایداری ماندن قابلیت احتراق در مکروکامباستور کمک می‌کند.