NUMERICAL INVESTIGATION OF AIR INJECTION DURING BIOMASS GASIFICATION IN A TWO-STAGE DOWNDRAFT CONFIGURATION

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ABSTRACT

The partial combustion in a two-stage downdraft gasifier is critical for the process optimisation. The hot zone is indeed determining for tar cracking, the major issue in gasification. The conditions in this zone are strongly influenced by the way of injecting air inside the gasifier.

In this paper, numerical simulations of the reactive flows within the oxidation zone are performed to characterise the influence of the injection surface area and the nozzle geometry on the process. Results show a transition in the flow pattern at an injection velocity around 34 m/s. Once this limit is reached, the nozzles suck up all the pyrolysis gas. Thus, it passes through a very hot zone, for an efficient tar cracking. Further increase in injection velocity accelerates the gas velocity in the hot zone. As a consequence, the residence time is shortened and the tars are less cracked.

The main conclusions of this study can be summed up in three observations:
• Air injection velocity determines the velocity in the combustion zone and thus the gas residence time in the hot zone;
• A minimum injection velocity of about 34 m/s is necessary to guarantee a satisfactory flow pattern and a homogeneous temperature in the hot zone; above this level temperature profile remains almost unchanged whatever velocity is used;
• Injection at a 34 m/s velocity and at an inclination of 5-10° from the vertical was found to be the optimum configuration studied.
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Abstract
The partial combustion in a two-stage downdraft gasifier is critical for the process optimisation. The hot zone is indeed determining for tar cracking, the major issue in gasification. The conditions in this zone are strongly influenced by the way of injecting air inside the gasifier.

In this paper, numerical simulations of the reactive flows within the oxidation zone are performed to characterise the influence of the injection surface area and the nozzle geometry on the process. Results show a transition in the flow pattern at an injection velocity around 34 m/s. Once this limit is reached, the nozzles suck up all the pyrolysis gas. Thus, it passes through a very hot zone, for an efficient tar cracking. Further increase in injection velocity accelerates the gas velocity in the hot zone. As a consequence, the residence time is shortened and the tars are less cracked.

Introduction
The energy crisis of the 1970s sparked a renewed interest on biomass gasification systems. Nowadays environmental concerns are questioning the continued use of fossil fuels and the need for sustainable energy production has prompted new research into the possibility of gasification as a key source for energy production.

Gasification is a thermal process converting biomass feedstock into a mixture of gases that can be burnt in boilers, internal combustion engines and gas turbines. If well designed, gasification allows an environmentally friendly energy production. Furthermore, it can help in reducing the “waste disposal” constraints by using it as a feedstock to convert it into useful and valuable product. Biomass is indeed a particular kind of fuel. Its price is fixed by the collecting expenses. That is why small-scale installations are well adapted to this market. They allow valorising wastes directly on their production location. However, tar, produced during the pyrolysis step, remains the “Achilles’ heel” of gasifiers because of the significant gas cleaning cost induced, the fouling problems and the efficiency loss [1].

In these perspectives downdraft gasifiers present indisputable advantages [2]. In current pilots called two-stage, drying/pyrolysis and combustion/reduction zones are physically separated. This low tar level technology requires only a small gas-cleaning unit to prevent engine fouling problems [3]. Furthermore it is well adapted to turnover and biomass diversity. Finally its utilisation is relatively easy and can be highly automated. However available kinetics data and the theoretical comprehension of the physical phenomena remain still insufficient to build a general accurate model.
In a two-stage downdraft gasifier, tar cracking mostly occurs in the partial combustion hot zone and in a smaller magnitude in the char bed [3]. The physical conditions inside the combustion zone depend on many parameters such as the quality of the pyrolysis gas, the air-fuel ratio, the gasifier geometry or the air injection velocity.

A CFD model for the combustion zone was previously developed [4] and validated with the experimental data got from the DTU 100 kWth two-stage gasifier [5,6]. It includes detailed chemical mechanism with tar cracking, heat transfer with radiation and turbulent fluid flow. It was used for a brief study of sensitivity for different parameters that enlightened the influence of the air injection on tar cracking. Thus, this paper analyses more deeply the role played by the air injection surface area and by the inclination of the nozzles. Comparison between different configurations is done in order to understand better the physical behaviour of gasifiers in the oxidation zone. In this paper, the model is firstly described. The results are then presented and commented. Finally conclusion on the gasifier design is made.

**Model**

The model is divided into three parts: fluid flow, chemical mechanism and heat transfer. Model equations are listed in Table 1. Figure 1 shows the 2D axisymmetric geometry of the computational domain and boundary conditions. Special interest is given to gas flows. Char particles fall fast on the fixed bed, with a residence time in the oxidation zone shorter than 0.1s. As a consequence heterogeneous reactions are negligible in the oxidation zone, as oxygen reacts so quickly with gas phase. Moreover particles also play only a minor role in heat transfer and gas flows, as shown by the previous tests [4]. They are also neglected in this study.

---

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>External convective heat transfer coefficient:</td>
<td>$h = 8 \text{ W.m}^{-2}.\text{K}^{-1}$</td>
</tr>
<tr>
<td>Insulation:</td>
<td>$100 \text{ mm} \ (k = 0.25 \text{ W.m}^{-1}.\text{K}^{-1})$</td>
</tr>
<tr>
<td>External emissivity:</td>
<td>$0.1$</td>
</tr>
<tr>
<td>$T_{\text{ext}}$</td>
<td>$300 \text{ K}$</td>
</tr>
</tbody>
</table>

**Figure 1.** Studied geometry and boundary conditions

**Pyrolysis gas + steam inlet**

- $U_x = 0.52 \text{ m/s}$
- Turbulence intensity: 3%
- $T = 923\text{K}$
- Hydraulic diameter: $\phi = 0.26 \text{ m}$

**Air inlet**

- $U_r = 20 \text{ to } 85 \text{ m/s}$
- $U_x = -40 \text{ to } 0 \text{ m/s}$
- Turbulence intensity: 31%
- $T = 890\text{K}$

**Wall heat transfer**

- External convective heat transfer coefficient: $h = 8 \text{ W.m}^{-2}.\text{K}^{-1}$
- Insulation: $100 \text{ mm} \ (k = 0.25 \text{ W.m}^{-1}.\text{K}^{-1})$
- External emissivity: 0.1
- $T_{\text{ext}} = 300 \text{ K}$
**Fluid flow**

Air is injected into the reactor through three injectors with five nozzles each. Reynolds number is around 2,000 at the air injector nozzles. The flow may thus be turbulent in this zone. Moreover velocity pattern is complex as recirculation may occur. A detailed turbulence model is thus required to simulate these phenomena. After a preliminary sensitivity study, the RNG k-ε model was chosen as the best compromise between accuracy and efficiency. It is also adequate for simulating relaminarised flow that may develop inside the gasifier [7]. Wall boundary conditions are simulated by a low Reynolds number approach detailed in [8].

**Chemical mechanism**

The chemical mechanism consists of five oxidation reactions (1-5) and the water-gas shift reaction (6).

\[
\begin{align*}
\text{CO} + 0.5 \text{O}_2 & \rightarrow \text{CO}_2 \\
\text{CH}_4 + 1.5 \text{O}_2 & \rightarrow \text{CO} + 2 \text{H}_2\text{O} \\
\text{H}_2 + 0.5 \text{O}_2 & \rightarrow \text{H}_2\text{O} \\
\text{C}_6\text{H}_6 + 4.5 \text{O}_2 & \rightarrow 6 \text{CO} + 3 \text{H}_2\text{O} \\
\text{C}_{10}\text{H}_8 + 7 \text{O}_2 & \rightarrow 10 \text{CO} + 4 \text{H}_2\text{O} \\
\text{CO} + \text{H}_2\text{O} & \leftrightarrow \text{CO}_2 + \text{H}_2
\end{align*}
\]

Arrhenius rate is calculated from equation (7).

\[
k_c = k_a e^{E_a/RT} [A]^a[B]^b \tag{7}
\]

Constants are taken from literature. They are listed in Table 2. The reverse term of (6) is obtained by a free Gibbs energy variation method. Tars, reduced to the only benzene and naphthalene, are modelled as a simplification of Jess works [9]. The tar-cracking model is not yet precise enough. But as the model is the same for each tested configuration, the comparison of their effect on tar cracking is possible and gives a first approximation to determine its quality. Detailed chemical model and discussion can be found in previous publication [4]. Since the flow is turbulent, it must be taken into account in the chemical reaction model. The chosen model, called “Eddy Dissipation Concept” model [10], calculates also Arrhenius rate at the turbulence time scale (17). It seems to suit well to this kind of reactive flow [11].

**Heat transfer**

As temperature exceeds 1,000°C in the reactor core, heat transfer by radiation is predominant. They are simulated by the Discrete Ordinates model [12] by discretizing space in four directions. It integrates the Radiative Transfer Equation (13). As a result, a source term $S_r$ due to radiative transfer is included in the energy equation (12). $S_r$ also includes the heat of the chemical reactions from equation (8).

\[
S_{r,e} = -\sum_j \left( \frac{h_j}{M_j} + \int_{t_{old}}^T c_{p,j}dT \right) R_{j,e} \tag{8}
\]
The absorption coefficient of the fluid phase is computed by the cell-based Weighted-Sum-of-Gray-Gases model [13]. It only takes into account the concentration of CO$_2$ and H$_2$O.

**Air injection simulation**

Simulation is 2D axisymmetric to take into account of the gasifier cylindrical geometry. for this purpose, the air injector, which is composed of five cylinders with three nozzles each, is considered as annular. Flowrate and injection surface area are conserved. Thus momentum is also conserved. Previous studies showed that this analogy was correct in this kind of problem [14]. It was also validated with the experimental data got from the DTU 100 kW$_{th}$ two-stage gasifier [4], although swirl neglecting may be a source of error.

Numerical simulation of the injection nozzle is difficult because of the difference in characteristic length: 1mm for the nozzle, 1m for the gasifier. The high velocity in the nozzle requires very fine mesh. This mesh applied to the whole process is however too computation-time costly for a practical application and too high difference in mesh size can not guarantee the validity of the results. To handle this problem, a simulation of the nozzle alone has been separately done to determine precise gas temperature and velocity at the nozzle exit. Boundary conditions as wall temperature are estimated from the previous simulation of the downstream injection. Air flowrate is set constant. Five different injection surface areas are tested (from 207 to 778 mm$^2$). For each surface area, the average injection velocity is calculated as $U_{inj} = \frac{\dot{q}}{\rho A}$. It is then decomposed into its two direction components, $U_x$ and $U_r$, which depend on the desired inclination angle. It varies from 0 to 45°. $U_x = 10$ m/s corresponds to an inclination of respectively 23°, 16° and 7° for $U_{inj} = 23, 34$ and 85 m/s. These values are then used in the gasifier model where the nozzle outlet is modelled as a velocity inlet with fixed values of both axial and radial velocity. On the whole, 15 different configurations have been tested. Figure 2 illustrates the air injection boundary condition principles.

$$U = \frac{\dot{q}}{\rho A}$$

**Numerical method**

A segregated solver solves sequentially the continuity, momentum (Navier-Stokes equations), energy, radiation and species equations (N-1 equations for N species). Governing equations are converted to algebraic equations that can be solved numerically by a control-volume-based technique through a power-law scheme [15]. SIMPLEC algorithm couples velocity and pressure [16]. The unstructured grid is composed of 30,000 cells. Meshing tests have been performed from 5,000 to 50,000 cells. The independence of results has been observed between 30,000 and 50,000 cells. Simulation is considered as converged when residuals remain constant at a value below $10^{-5}$ ($10^{-4}$ for momentum). The calculation time is approximately 48 hours on a 3.2 GHz computer.
Mass \[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \] (10)

Momentum \[ \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\vec{F}) + \rho \vec{g} + \vec{F} \] (11)

Energy \[ \frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\vec{v} (\rho H + p)) = -h \rho \frac{\partial \vec{v}}{\partial t} - \sum_j h_j \vec{\beta}_j + \nabla \cdot (\vec{F} \vec{v}) + S_f \] (12)

With \[ H = \sum_i Y_i h_i = \sum_i Y_i \int_0^T c_p \,dT ; \quad k_{\text{eff}} = k + k_i ; \quad k_i = \frac{\nu_i c_p}{P_r} \] [6].

Radiative transfer \[ \nabla (I(\vec{r}, \vec{s}) \Phi) + (\alpha + \sigma_s) I(\vec{r}, \vec{s}) = \alpha n \frac{8 \pi T^4}{\pi} + \frac{\sigma_s}{4 \pi} \int_0^{2 \pi} I(\vec{r}, \vec{s}) \Phi(\vec{s}, \vec{s}') d\Omega' \] (13)

Turbulence \[ \frac{\partial}{\partial x_j} \left( \rho U_j \frac{\partial \rho}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left[ \rho \alpha_k \frac{\partial \rho}{\partial x_j} \right] + \rho \nu_i \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \rho \epsilon \] (14)

\[ \frac{\partial}{\partial x_j} \left( \rho \alpha_k \frac{\partial \rho}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \rho \alpha_k \frac{\partial \rho}{\partial x_j} \right) + C_{\epsilon_1} \frac{\epsilon}{k} \rho \nu_i \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} - C_{\epsilon_2} \rho \frac{\epsilon^2}{k} - \rho \] (15)

With \[ \nu_{\text{eff}} = \nu \left( 1 + \frac{C_{\mu}}{\nu} \frac{k}{\sqrt{\epsilon}} \right)^2 = \nu \left( 1 + \frac{\nu}{\nu} \right)^2 \]

\[ C_{\mu} = 0.0845; C_{\epsilon_1} = 1.42 \text{ and } C_{\epsilon_2} = 1.68. \alpha_k \text{ and } \alpha_\epsilon \text{ are the inverse of turbulent Prandtl number for } k \text{ and } \epsilon. \]

Species transport \[ \frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \left( -\left( \rho D_{0,i} + \frac{\mu_i}{S_{c_i}} \right) \nabla Y_i \right) + R_i \] (16)

Homogeneous reaction rate \[ R_{r,i} = \frac{(\xi^*)^2 \chi}{\tau^*} (Y_i^* - Y_i) \] (17)

With \[ \xi^* = C \left( \frac{\nu \epsilon}{k^2} \right)^{0.5}; \quad \chi = \frac{\rho}{[1 - (\xi^*)^3]} ; \quad \tau^* = C \left( \frac{\nu \epsilon}{k^2} \right)^{0.5} \]

\[ C = 2,1377 ; C = 0,4082. \]

**Table 1. Governing equations**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$k_s$ (homogeneous unity)</th>
<th>$E_a$ (J. kmol$^{-1}$)</th>
<th>A</th>
<th>B</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>$1.3 \times 10^{11} \times [\text{H}_2\text{O}]^{0.5}$</td>
<td>$1.256 \times 10^8$</td>
<td>1</td>
<td>0.5</td>
<td>Shin [17]</td>
</tr>
<tr>
<td>(2)</td>
<td>$4.4 \times 10^{11}$</td>
<td>$1.2552 \times 10^8$</td>
<td>0.5</td>
<td>1.25</td>
<td>Jones [18]</td>
</tr>
<tr>
<td>(3)</td>
<td>$4.462 \times 10^{12}$</td>
<td>$4.2 \times 10^7$</td>
<td>1</td>
<td>1</td>
<td>Di Blasi [19]</td>
</tr>
<tr>
<td>(4)</td>
<td>$2.4 \times 10^{11}$</td>
<td>$1.2552 \times 10^8$</td>
<td>1$^a$</td>
<td>1.85</td>
<td>Westbrook [20]</td>
</tr>
<tr>
<td>(5)</td>
<td>$9.2 \times 10^5 \times T$</td>
<td>$8 \times 10^7$</td>
<td>0.5</td>
<td>1</td>
<td>Di Blasi [19]</td>
</tr>
<tr>
<td>(6)</td>
<td>124.03</td>
<td>$1.26 \times 10^7$</td>
<td>1</td>
<td>1</td>
<td>Di Blasi [19]</td>
</tr>
</tbody>
</table>

$^a$: modified

**Table 2. Reference values for kinetic constants**
Results & Discussion

Temperature profile

The main point regulating the gasification process quality is the tar elimination. In this perspective two "primary" reactions, i.e. inside the gasifier, are used: thermal cracking without catalyst in the oxidation zone and catalytic cracking in the fixed bed.

This paper aims to analyse finely only the oxidation zone, particularly in function of the way in injecting air. From experimental observations in a two-stage downdraft gasifier, this zone is the most important in tar cracking. The concentration of the tars produced during pyrolysis is indeed divided in this zone by 100 [3]. It is again divided by 20 in the reduction zone.

Obviously the most important factor in thermal cracking seems to be temperature. Literature reports that the minimum temperature required to crack tars without catalyst is 1,000 – 1,100°C or even 1,500°C in some special configuration [21]. In this study the threshold temperature required for thermal cracking is fixed to 1,100°C that appears to be the most common value.

The first step of the analysis is also to characterise the zone of the gasifier where temperature exceeds 1,100°C, called hot zone. Figure 3 represents this critical part in three different configurations. It is observed that the influence of the injection nozzles is limited as soon as the velocity exceeds about 30 m/s. Higher velocity increases the hot zone surface after the throat. Axis temperature reaches earlier 1,100°C. Temperature profile for small velocity (22 m/s) is different because of a significant flow pattern change: junction between injected air occurs deeper in the gasifier and there is no recirculation along the walls of the hot zone.

Flow pattern and gas residence time at high temperature

The second most influencing parameter in tar cracking is the residence of gas inside the hot zone. The streamlines of the flow are used to visualise gas path. It can be seen in Figure 4. Pyrolysis gas is “sucked” up by the depression due to the high velocity injection. It is then entrained and accelerated by the airflow. The velocity of gas in the hot zone is only dependent of the air injection velocity at constant pyrolysis gas flowrate. But in every case residence time in the hot zone is low, inferior to 0.1s. The transition between 22 m/s and 34 m/s is very
clear. The chock between the slow pyrolysis gas and the very quick air flow becomes strong enough to disturb totally the pyrolysis gas flow along the axis when injection velocity reaches 34 m/s. Higher velocity increases the unused volume just above injection.

Figure 5 shows the temperature evolution of the gas during its path in the whole gasifier but without char bed the gas. The gas path strongly depends on the initial departure point. That is why average time between paths 1-7 is employed in Figure 6 to determine the mean time where gas temperature exceeds 1,100°C. As soon as velocity reaches 34 m/s, higher air injection velocity induces smaller residence time of combustion gas in the hot zone. Indeed the slight increase of the hot zone surface is not sufficient to compensate the reduction of the combustion gas velocity. Below 34 m/s, the nozzle does not suck up strong enough the pyrolysis gas; its path is thus shorter.

Figure 4. Streamlines ($U_x = 0$ and $U_r = (a) 23$ or (b) $34$ or (c) 85 m/s at the nozzle exit)

Figure 5. Evolution of gas temperature ($U_x = 0$ and $U_r = 22$ m/s at the nozzle exit)
Flow is fully turbulent in the injection zone, the maximum turbulence intensity exceeding 500% in every case. Turbulence intensity increases with increasing radial and axial injection velocity. Increase in injection velocity leads to higher turbulence level but also to lower reaction rate. Better mixing does not compensate the decrease of the residence time. It thus seems that the reaction rates are kinetically controlled in the oxidation zone.

Air flowrate and axial injection velocity influence

Previous simulations have been performed with a straight annular nozzle, perpendicular to the flow. In order to simulate an inclined nozzle, an axial injection initial velocity has been added. As it is opposed to the pyrolysis gas flux, its value is negative.

Results show that the moderate inclination has a positive impact on the process. Even if it accelerates slightly the flow in the hot zone, it reduces the unused volume above the injector. It thus decreases the transition velocity between the two flow patterns, as shown in Figure 7. Moreover a slightly greater part of the gas recirculates in this zone at relatively high temperature, about 1,000°C. Besides the counter-flow injection increases turbulence level and favours air and pyrolysis gas mixing. As a result, temperature is more homogeneous in the hot zone. However, it also increases the axial gas velocity in this zone of about 10% (i.e. –10m/s axial injection velocity leads to a 1 m/s increase of axial gas velocity). As a consequence residence time is reduced a little. But positive effects counterbalance this inconvenient in terms of naphthalene cracking as can been seen in Figure 8. Inclination of more than 16° from the vertical results in a highly turbulent and hot zone close to the nozzle, particularly favourable for tar cracking. However this zone is not big enough to include the gasifier centre. As a result part of pyrolysis gas goes straight along the central axis, as it was observed for injection velocity below 34 m/s (see Fig. 4). The optimal inclination depends of injection velocity and is comprise between 5° and 10° (i.e. 3 < U_x < 6 m/s) for U_{inj} = 34 m/s.

To determine the air mass flowrate influence, injection surface area has been kept constant while varying radial injection velocity (-/+ 10%). Axial injection velocity remains
null. Increasing air/fuel ratio leads to increasing heat released from combustion. As a result the hot zone is bigger, as shown in Figure 8, and the tar cracking becomes more complete, even if the residence time is significantly reduced. Flow pattern is mainly influenced by the air injection velocity. Air/fuel ratio has to be fixed on the minimum value to allow a sufficient heat release so that the output gas LHV would be maximum.

Figure 7. Effect of axial injection velocity on massless particles pathlines ($U_{\text{inj}} = 34 \text{ m/s}$)

Figure 8. Effect of air flowrate on the hot zone ($U_{\text{inj}} = 60 \text{ m/s}, U_{\text{inj,x}} = 0 \text{ m/s}$)
**Reaction rate**

In order to compare the efficiency in terms of tar cracking, a comparison between the volumetric integral of naphthalene thermal cracking is done on the whole computational domain. This value is directly proportional to the tar reduction in the oxidation zone, as reduction reactions are not considered in this study. These values, plotted in adimensional form \( R = \frac{R_{inj}}{Max(R_{inj})} \) in Figure 9, give a trend to determine the tar cracking quality.

It appears that a maximum is obtained for a 34 m/s injection. These results are in agreement with Venselaar’s conclusions reported in FAO report [22] that recommend a nozzle air inlet velocity around 30 - 35 m/s for Imbert type gasifier. Below this value, the flow pattern allows a part of pyrolysis gas to pass through a reduced temperature zone. As a result, a fraction of tar is not cracked. Above this value, temperature stays relatively homogeneous inside the gasifier but the pyrolysis gas go faster in the hot zone. The residence time is then too low to guarantee a total tar cracking. Fig. 6 and 9 show a high similitude: residence time and naphthalene thermal cracking are almost directly linear in function of injection velocity with a slope slightly greater for naphthalene cracking. Residence time also seems to be the main parameter influencing tar cracking. Besides moderate injection inclination considerably improves naphthalene thermal cracking.

![Figure 9. Influence of injection velocity on naphthalene thermal cracking](image)

**Conclusion**

The objective of this study was to analyse the influence of the air injection surface area in a two-stage downdraft gasifier. It is indeed a fundamental point to determine the process efficiency in terms of tar cracking.

A 2D axisymmetric CFD model was used to compare the different configurations. Interesting observations were found:
Air injection velocity determines the velocity in the combustion zone and thus the gas residence time in the hot zone;

A minimum injection velocity of about 34 m/s is necessary to guarantee a satisfactory flow pattern and a homogeneous temperature in the hot zone; above this level temperature profile remains almost unchanged whatever velocity is used;

Injection at a 34 m/s velocity and at an inclination of 5-10° from the vertical was found to be the optimum configuration studied.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[A]</td>
<td>Concentration of species A [kg. m⁻³]</td>
</tr>
<tr>
<td>c_p</td>
<td>Specific heat [J. kg⁻¹. K⁻¹]</td>
</tr>
<tr>
<td>E_a</td>
<td>Activation energy [J. kmol⁻¹]</td>
</tr>
<tr>
<td>h</td>
<td>Heat transfer coefficient [W. m⁻². K⁻¹]</td>
</tr>
<tr>
<td>h°</td>
<td>Standard state enthalpy [J.kg⁻¹]</td>
</tr>
<tr>
<td>I</td>
<td>Radiative intensity [W. m⁻²]</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity [W. m⁻¹. K⁻¹]</td>
</tr>
<tr>
<td>k_s</td>
<td>Frequency factor [homogeneous dimension]</td>
</tr>
<tr>
<td>k_c</td>
<td>Arrhenius kinetic rate [s⁻¹]</td>
</tr>
<tr>
<td>k_m</td>
<td>Mass diffusion coefficient [kg.m⁻².s⁻¹]</td>
</tr>
<tr>
<td>m</td>
<td>Mass [kg]</td>
</tr>
<tr>
<td>M</td>
<td>Molar weight [kg. kmol⁻¹]</td>
</tr>
<tr>
<td>P</td>
<td>Pressure [Pa]</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandt number</td>
</tr>
<tr>
<td>R</td>
<td>Ideal gas constant [8.314 J. kmol⁻¹]</td>
</tr>
<tr>
<td>R_i,r</td>
<td>Homogeneous reaction rate [kg. m⁻³.s⁻¹]</td>
</tr>
<tr>
<td>T</td>
<td>Temperature [K]</td>
</tr>
<tr>
<td>U</td>
<td>Velocity [m.s⁻¹]</td>
</tr>
<tr>
<td>Y</td>
<td>Mass fraction, ( Y_i = \frac{m_i}{m_{total}} )</td>
</tr>
<tr>
<td>α</td>
<td>Absorption coefficient [m⁻¹]</td>
</tr>
<tr>
<td>α_Pr</td>
<td>Inverse of the turbulent Prandtl number</td>
</tr>
<tr>
<td>ε_m</td>
<td>Emissivity</td>
</tr>
<tr>
<td>φ</td>
<td>Hydraulic diameter [m]</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity [m². s⁻¹]</td>
</tr>
<tr>
<td>ρ</td>
<td>Density [kg. m⁻³]</td>
</tr>
<tr>
<td>σ_S</td>
<td>Scattering coefficient [m⁻¹]</td>
</tr>
<tr>
<td>σ</td>
<td>Boltzmann constant [5.67×10⁻⁸ W.m⁻².K⁻⁴]</td>
</tr>
</tbody>
</table>

**Subscripts**

- eff: effective
- i: species i
- inj: injection
- r: Radial co-ordinate [m]
- t: turbulent
- x: Axial co-ordinate [m]
References