



Numerical investigation of the burning characteristics of ventilation air methane in a combustion based mitigation system



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HIGHLIGHTS

- A new combustion mitigation system of ventilation air methane is numerically studied.
- The effects of preheating and methane concentration are revealed.
- Preheating has a significant influence on the oxidation of ventilation air methane.
- Combustion of mixtures with high methane concentration is more unsteady and vortical.

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ABSTRACT

Large-eddy simulation of the reacting flow field in a combustion-based mitigation system to reduce the emissions of methane contained in ventilation air methane is presented. The application is based on the preheating and combustion of ventilation air methane. Effects of preheating and methane concentration are examined in five computational cases. The results indicate that the oxidation of the ventilation air methane can take place in a co-annular jet configuration provided that the preheating temperature is as high as 500 K for mixtures containing a low methane concentration of 0.5%. It is found that the oxidation process that eventually leads to reaction and combustion is controlled by the methane concentration and the level of preheating.

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1. Introduction

Methane is a greenhouse gas (GHG) with a global warming potential (GWP) that varies over the atmospheric residency time [1]. Upon release to the atmosphere and using a reference value of unity for carbon dioxide, the GWP is initially 56 over the first 20 years, 21 over 100 years and 6.5 over 500 years. The radiative forcing factor of methane is second only to that of carbon dioxide. These two attributes are central to the argument that methane released to the atmosphere has an immediate effect far more intense than that of the carbon dioxide release and could be responsible for creating a short-term high temperature perturbation or positive feedback loop [2–4]. Therefore, reduction of methane releases to the atmosphere is essential to minimize these global hazards. Besides, the absence of mitigation actions not only

increases the global warming effect, but also has economical implications [5].

The atmospheric concentration of methane associated with coal mining is estimated to be about 15% of the total anthropogenic methane produced, while coal handling, abandoned underground mines and surface mines represent about 26% of the total emissions [6]. The largest fraction of atmospheric methane from coal mining activities is due to the release of ventilation air methane (VAM) [7]. Methods to mitigate VAM are desirable from a global climate perspective and could be economical if the energy contained in the ventilation flow is captured. Since methane is a high impact GHG, VAM from coal mining operations or abandoned mines should be targeted for mitigation and for the development of cost effective technologies for mitigation [8].

VAM has been difficult to exploit because it is a low methane concentration high volumetric flow case. A number of technologies have been developed to mitigate VAM and there are essentially two basic methods for the mitigation and utilization of VAM: ancillary and principal uses [9]. Ancillary use is referred to as the use of

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VAM as an oxidizer instead of ambient air in combustion engines, gas turbines or rotary kilns to improve combustion performance [10,11]. When the VAM replaces air in a combustion process, it is employed as a secondary fuel residing in the intake air. Higher concentration sources of methane, such as drained sources are either flared or sold to the market [9]. The principal uses for VAM as a primary fuel can be found in thermal flow reverse reactors, catalytic flow reverse reactors, lean burn gas turbines (GTs), recuperative GT or regenerative thermal oxidation [12,13]. In these instances, the VAM is oxidized when it comes in contact with ceramic beads or rock particles at a sufficiently high temperature. These systems usually require an external energy source to raise the temperature to the operating point and then it becomes sustainable as the VAM is consumed [14]. The addition of catalysts serves to reduce the oxidation temperature, but catalysts are expensive and may require replacement.

Mitigation systems based on the oxidation of the low concentration methane contained in VAM mixtures have some potential for power generation [7]. A technology based on VAM oxidation, the VamTurBurner (C) currently being developed [7], uses waste heat from gas turbine exhaust to preheat the VAM and requires a second preheating stage, where energy is drawn from downstream by a heat exchanger or recirculation system to preheat the VAM further. This configuration allows a rise in temperature to a state such that the methane may be oxidized by an igniter flame. This new multi-generation system [7] uses the total heat from a cogeneration cluster, igniters and VAM as a heat source for the production of more electricity, industrial drying, hot water, heating or cooling. These thermal outputs of the multi-generation system might be available to other industries or to a community depending on proximity and demand. The preheating of the VAM is essential to the combustion process, since it contributes to flame stability and allows the ignition to take place under restrictive operating conditions and for ultra-lean mixtures.

The study of the combustion characteristics of ultra-lean mixtures is still at an early stage. Some groups have studied the combustion of ultra-lean hydrocarbon mixtures reporting the oxidation of the mixtures under certain conditions. A comprehensive analysis of the chemical kinetics involved in the ignition of ultra-lean methane for catalytic combustion was undertaken in the work by Wang et al. [15] for the mixtures of interest here. Ignition in ultra-lean mixtures by extending the flammability limit has also been reported using subcritical microwaves [16] and preheating [17,18]. The work by Cheng et al. [19] showed that preheating extended the flammability limit for ultra-lean methane mixtures. The fuel oxidation takes place after the interaction with hot combustion products. Analysis of the flame structure for different mixtures and levels of flame stretch are found in the literature [20,21]. It was reported that ignition was very sensitive to the amount of preheating, concentration and flame stretch. Simple flame configurations have been investigated using detailed chemistry in the literature [20,21], but to the authors knowledge, the interaction of ultra-lean mixtures with a well-established turbulent flame has not been addressed.

This study aims to investigate the oxidation process and the dynamics of VAM mixtures interacting with the heat release at different preheating temperatures and methane concentrations for a simplified combustor configuration. The concept of large-eddy simulation (LES) is employed in the present work and similar reacting conditions as those found in mild combustion [22,23] are investigated here. The difference in this case is that there is no recirculation zone to mix reactants and products to achieve lean premixed conditions, since the lean homogeneous fuel mixture or VAM is directly supplied. The challenges of this configuration are associated with finding adequate operating conditions (preheating temperature and fuel concentration) for low concentration

methane streams, so that VAM mixtures can be burnt in practical combustors.

This paper starts with an introduction of the background and motivation of the study. It is followed by the description of the governing equations and the theoretical aspects of the numerical strategy, while results for instantaneous and time-averaged flow fields are described and analyzed subsequently. Finally, some conclusions and directions for future work are also given.

2. Mathematical modelling

The analysis of the combustion dynamics of mixtures containing different methane concentrations is addressed here using large-eddy simulation. In LES, the large-scale structures of the flow are resolved by governing equations, while the small-scales are modelled using closure rules [24]. The flow field is filtered in space using a box filter given by $\Delta = V^{1/3}$, where V represents the cell volume.

In order to reduce the complexity of filtering variables with density variations, a Favre-averaged filtering is employed [25]. The filtering process is given by $\bar{f} = \overline{\rho f / \rho}$, where ' $\bar{\cdot}$ ' is used for space-filtered quantities and ' $\tilde{\cdot}$ ' for Favre-averaged variables. The LES governing equations for multi-species reacting compressible flows are presented in the next section, which include the conservation of mass, momentum, energy and species mass fractions respectively.

2.1. LES governing equations

The filtered governing equations for LES are given by:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial (\bar{\rho} \tilde{u}_j)}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial (\bar{\rho} \tilde{u}_i)}{\partial t} + \frac{\partial (\bar{\rho} \tilde{u}_j \tilde{u}_i)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \bar{\tau}_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}^{sgs}}{\partial x_j} \quad (2)$$

$$\frac{\partial (\bar{\rho} \tilde{e})}{\partial t} + \frac{\partial (\bar{\rho} \tilde{u}_j \tilde{e})}{\partial x_j} = -\bar{p} \frac{\partial \tilde{u}_j}{\partial x_j} - \frac{\partial \bar{q}_j}{\partial x_j} + \bar{\tau}_{ij} \frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial h_j^{sgs}}{\partial x_j} + \Theta^{sgs} + \bar{Q}^c \quad (3)$$

$$\frac{\partial (\bar{\rho} \tilde{Y}_m)}{\partial t} + \frac{\partial (\bar{\rho} \tilde{u}_j \tilde{Y}_m)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\bar{\rho} \bar{D}_m \frac{\partial \tilde{Y}_m}{\partial x_j} \right) - \frac{\partial \Phi_{j,m}^{sgs}}{\partial x_j} + \bar{\rho}_m^c \quad m = 1, \dots, N \quad (4)$$

where $\bar{\rho}$, t , \tilde{u}_i , x_i , \bar{p} , $\bar{\tau}_{ij}$, \tilde{e} , \bar{q}_j , \bar{Q}^c , \tilde{Y}_m and $\bar{\rho}_m^c$ are the density, time, i th velocity component with $i = 1, 2, 3$ in Cartesian coordinates, pressure, stress tensor, internal energy, heat flux, combustion heat release, species mass fraction and the source term due to chemical reactions respectively. The index $m = (1 \text{ to } N)$ denotes the individual species, while the superscript *sgs* refers to the subgrid scale terms coming from the filtering process.

The filtered stress tensor $\bar{\tau}_{ij}$ is obtained neglecting the effect of the unresolved field [26] and is given by:

$$\bar{\tau}_{ij} = \bar{\mu} \left[\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) - \frac{2}{3} \frac{\partial \tilde{u}_k}{\partial x_k} \delta_{ij} \right] \quad (5)$$

where $\bar{\mu}$ represents the dynamic viscosity and δ_{ij} is the Kronecker delta. The temperature-dependent viscosity $\mu(T)$ is obtained from the Sutherland's law [27], while the filtered heat flux \bar{q}_j is given by:

$$\bar{q}_j = -\bar{K} \frac{\partial \tilde{T}}{\partial x_j} + \bar{\rho} \sum_{m=1}^N \tilde{h}_m \bar{D}_m \frac{\partial \tilde{Y}_m}{\partial x_j} \quad (6)$$

where \bar{K} , \tilde{T} , \bar{D}_m , and \tilde{h}_m are the filtered thermal conductivity, temperature, diffusion coefficient and enthalpy of species m respectively. The heat conductivity is obtained by providing a constant

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