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Burning rates and temperatures of flames in excess-enthalpy burners: A numerical study of flame propagation in small heat-recirculating tubes

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This study investigates flame propagation in small thermally-participating tubes where the wall acts as a heat-recirculating medium. This fundamental configuration allows heat in the combustion products to be recirculated into the reactants, resulting in excess enthalpy and enhanced burning rates. Preheating of the reactants by heat recirculation has traditionally been considered to be the dominant mechanism leading to large burning rates observed in such systems. This is mainly supported by results from physical models based on a one-dimensional (1-D) representation of the system, where the radial diffusion of heat from wall surface to channel centerline is not accurately captured. In this study, a 2-D formulation with conjugate heat transfer, which accurately resolves the transport of heat inside the gas-wall system, is used to model the excess-enthalpy phenomenon. Steadily-propagating stoichiometric methane–air flames are simulated inside an adiabatic tube of finite wall-thickness, over a wide range of inlet flow velocities and small tube diameters. Burning-rate enhancement is found to be caused not only by preheating, associated with heat recirculation, but also by an increase in flame-front area. Flame elongation is more pronounced with increasing tube diameter and inlet velocity, up to a point where the change in flame-front area becomes dominant in enhancing burning rate. In that case, heat recirculation is a necessary condition for flames to couple to the thermal wave in the wall and elongate, but does not provide a significant increase in enthalpy or temperature that would otherwise be needed for high burning rates to be observed. As the diameter is reduced, the effect of preheating becomes increasingly important for burning-rate enhancement compared to flame area increase. At very small diameters, smaller than the flame thickness, the increase in burning rate is seen to be predominantly attributable to preheating. However, preheating is seen to become limited as inflow velocity is increased, due to 2-D effects inside the fluid that interfere with heat recirculation. These findings demonstrate that 2-D effects inside the fluid can have a prohibitive influence on the burning-rate enhancement attributed to preheating, but that they also give rise to an additional mechanism, associated with the change in flame surface area, responsible for burning-rate enhancement in heat-recirculating burners.

1. Introduction

The concept of excess-enthalpy combustion has raised interest since it was initially proposed by Weinberg [1]. The concept is based on recirculating heat from combustion products to the unburnt reactants through a burner solid structure, in order to obtain an accumulation of enthalpy in the flame region. This can lead to superadiabatic flame temperatures, or temperatures higher than the adiabatic flame temperature predicted from the inlet conditions. This characteristic of the flame leads to several advantages in terms of combustion properties, as it increases the temperature-dependent reactivity of mixtures, extending conventional flammability limits [2]. A potential application for such combustion technology is the burning of low-calorific mixtures involving low-grade fuels, such as low-quality biogas, since these diluted mixtures require increased reactivity in order to become flammable [3]. Heat-recirculating burners can also be suitable for extending the rich flammability limit of hydrocarbon–air mixtures, which is needed for the production of hydrogen-rich syngas that can be utilized for efficient power production in hydrogen-operated fuel cells [4].

The potential for such technology is supported by various experimental results where extended flammability limits [3,4] and large burning rates [5,6] are observed. Many different burner configurations have been proposed, ranging from porous burners

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to swiss-roll combustors [7,8]. These configurations rely on combustion at the small scale, where the surface-to-volume ratio is large enough for sufficient heat transfer between the fluid and solid structure to occur. This underlines the importance of modeling heat transfer accurately in order to come up with a predictive theory for heat-recirculating burners.

Using a basic model similar to Mallard and Le Chatelier [9], Leach et al. [10] considered a flame stabilized in a small channel, where heat recirculation through the wall occurred in conjunction with upstream heat diffusion inside the gas. Their analysis showed an increase in the effective diffusivity of the flame due to high wall thermal conductivities, which enhances burning rate. Increased burning rates are, therefore, predicted to be caused by the combined effects of increased effective diffusivity and increased reactivity due to high temperatures. These effects both originate from the preheating of reactants via heat recirculation.

Most models capturing these effects of heat recirculation on flames are based on one-dimensional (1-D) formulations, where the flow is volumetrically averaged over the channel cross-section. Asymptotic flame models, where the reaction zone is modeled as a jump condition, have been used to predict flame behavior over a wide parameter range [11–14]. Various trends observed experimentally are successfully reproduced by these models [4,13,15]; however, quantitative agreement between asymptotic predictions and experiments is not observed. This is not surprising considering the high level of simplification involved in asymptotic model formulations.

More accurate 1-D models with detailed chemistry can also be used. These 1-D numerical models provide satisfactory agreement with experimental data at specific test conditions [16,17]. For the volumetric averaging in 1-D models to be acceptable, the transverse, or radial, diffusion of heat from wall surface to channel centerline should not be a limiting process, as this diffusion is assumed to be instantaneous over the channel cross-section. For this assumption to hold, the characteristic channel size should be small enough compared to the flame thickness, such that the flame structure can be assumed to be more or less flat and perpendicular to the incoming reactant stream, as commonly assumed for micro- and meso-scale channels. However, flames in small flow passages can become significantly curved as parameters, such as diameter and inlet velocity, are varied [18,19]. Axially-distributed, two-dimensional flame structures may have a significant impact on the energy distribution inside the system, which can, in turn, impact the preheating effect on which excess-enthalpy combustion relies.

Detailed, multi-dimensional models are needed to predict the full features of flame structure. Multi-dimensional models are much more computationally expensive than 1-D models, such that they are typically used with reduced chemistry over a limited range of conditions. Studies have looked at the propagation of flames in small channels and multiple flame structures have been reported involving elongation [20], partial quenching [21], and tip-opening [22]. However, only a few multi-dimensional studies have included the effect of conjugate heat transfer to capture the flame-wall thermal coupling occurring in small channels [23–26]. Elongated flame shapes are reported, but their effect on the heat distribution leading to burning-rate enhancement is not specifically investigated.

There is a need to determine the significance of two-dimensional effects on burning-rate enhancement phenomena observed in heat-recirculating burners, as these effects are expected to have an impact on the energy distribution inside the system. This can, in turn, affect the preheating of reactants leading to excess-enthalpy flames. This approach is particularly important as parameters known to influence flame shape, such as inlet velocity and channel size, are central in the design and operation of excess-enthalpy burners.

In this study, a system consisting of an adiabatic tube of circular cross-section, in which a flame is allowed to propagate, is investigated numerically. In this system, the tube wall can recirculate heat axially, and is known to provide conditions for excess-enthalpy burning in steadily-propagating flames [27,13]. A two-dimensional model for reactive flow with conjugate heat transfer is used as the most accurate representation of the system, as it can accurately capture the relevant 2-D effects that may influence flame shape, energy distribution, and burning-rate enhancement inside the system. Results are analyzed in order to assess flame structure and characteristics, as well as to determine the mechanism responsible for burning-rate enhancement. 2-D results are also compared with results from a 1-D model at similar conditions in order to assess the relative influence of 2-D effects on the system based on the relative deviations between model predictions. Simulations are performed over a wide range of inlet velocities and tube diameters in order to capture the different stable burning regimes known to occur in these systems, with particular attention to those involving flame-wall thermal coupling.

2. System of interest

The system of interest, shown in Fig. 1, consists of a flame propagating inside a tube of circular cross-section with finite wall thickness and an adiabatic external-wall surface. An inlet flow of a combustible stoichiometric methane–air mixture is imposed at the tube inlet with a velocity S_{in}, which corresponds to the mean velocity of a fully-developed parabolic profile. As the flame propagates inside the tube, the tube wall is locally heated by high flame temperatures. The flame propagation velocity S_p, in the reference frame of the tube, is the same as the velocity of the thermal wave traveling inside the wall because the flame and thermal wave are coupled. In the reference frame of the flame, the burning velocity of the flame, S_b, is the sum of S_{in} and S_p.

A notable study describing the behavior of this system is that of Ju and Xu [13], which determined the global nature of flame propagation with a one-dimensional asymptotic model. It is of interest to present predictions from this model as they are representative of the current understanding of the dominant physics involved in this heat-recirculating system, as the model captures the preheating effect leading to high burning rates. The theoretical model shows two possible solution regimes for fast- and slowly-propagating flames that depend on the applied inlet mass-flow rate. Figure 2 shows axial profiles of fluid and wall temperatures, deficient species, and total enthalpy at the different flame regimes occurring over a range of inflow velocities.

Fast flames are produced when the inlet velocity is small compared to the flame propagation speed. For these flames, the flame temperature is lower than the predicted adiabatic flame temperature of the initial mixture due to heat loss to the channel walls, whose temperature is almost unchanged by the flame. For zero

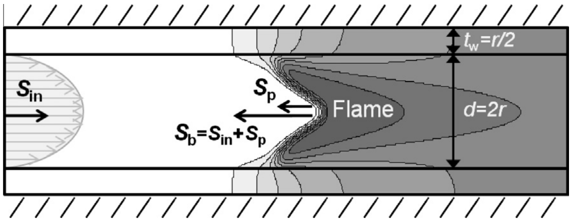

Fig. 1. System of interest: tube of circular cross-section of diameter d, with finite wall thickness, t_w, in which a flame propagates. The inlet velocity is denoted as S_{in}, which corresponds to the mean velocity of a fully-developed parabolic profile. Propagation speed is denoted as S_p and burning velocity as S_b. Typical temperature contours are shown in shades of gray.