Combustion and Flame 173 (2016) 27–38

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Effect of external heat loss on the propagation and quenching of flames in small heat-recirculating tubes

George P. Gauthier, Jeffrey M. Bergthorson*

Department of Mechanical Engineering, McGill University, Montréal, Quebec H3A 0C3, Canada

ARTICLE INFO

Article history:
Received 29 October 2015
Revised 24 July 2016
Accepted 26 July 2016
Available online 1 September 2016

Keywords:
Excess enthalpy
Heat recirculation
Micro-scale
Meso-scale
Extinction
Blowout

ABSTRACT

This study investigates the effect of external heat loss on the slow propagation of strongly-burning flames inside narrow heat-recirculating tubes. The system is studied using a two-dimensional numerical model for reactive flow, including conjugate heat transfer, over a range of tube diameters spanning the micro- and the meso-scale. Increasing external heat loss decreases the propagation speed of the slowly-propagating flames, leading to a transition from upstream to downstream propagation, until a heat loss limit is reached. Flames in micro-scale tubes are subjected to an extinction limit, while flames in larger diameter tubes, in the meso-scale range, are subjected to a blowout limit. While the absolute value of the external convective heat loss coefficient at the extinction/blowout limit increases with diameter, the dimensionless volumetric heat loss coefficient decreases with an increase in diameter until an approximately constant value, for the studied conditions, is reached at the blowout limit in the mesoscale range. Discrepancies in the predicted trends of 1-D and 2-D models indicate that 2-D effects play a significant role at larger diameters, not only at the meso-scale, but also in the upper-range of the micro-scale. These 2-D effects, associated with changes in flame shape that allow an increase in burning surface area, are seen to promote stability of the system. Results have implications on the choice of tube diameter to be used in the design of a stable burner optimized for heat transfer to an external heat load.

1. Introduction

Concerns about climate change and energy availability establish a need for alternative fuels to replace conventional fossil fuels. Under-utilized energy sources, such as biogas, syngas, landfill gas, and vented natural gas are promising alternatives [1–3]. Burner technologies are needed that can burn, directly, these mixtures of low heat content. Heat-recirculating burners, also referred to as excess-enthalpy burners [2], can increase the reactivity of mixtures, allowing the efficient burning of mixtures of low energy content [1].

Heat-recirculating burners rely on heat transfer via a solid structure to provide an alternate path, in addition to the gas path, for heat to reach unburnt reactants [2,4]. In order for interfacial heat transfer between wall and fluid to be sufficient for the flame behavior to be influenced by heat recirculation, the surface-to-volume ratio of the gas stream should be large enough, leading to small characteristic dimensions of the flow channel [4]. These small dimensions are additionally advantageous for transferring heat from the reacting mixture to an external heat load. This load could be a power conversion system, such as an external-combustion engine [5–7] or a thermoelectric device [8,9], whose efficiencies increase with heat source temperature [2,9]. Maximization of heat source temperature requires heat transfer to occur close to the flame zone, such that there is a need for characterizing the effect of external heat loss on excess-enthalpy flames.

The effect of heat loss on conventional flames propagating in small flow passages has been studied extensively since the original work done by Davy [10]. Flames do not propagate through a flow passage when the gap size is smaller than the quenching distance. This phenomenon can be captured using a one-dimensional (1-D) modeling approach [11,12] accounting for convective heat loss from the reacting fluid to a wall maintained at a constant temperature. Quenching is predicted to occur when the temperature-dependent heat release rates become too small to overcome heat loss across the flame [13]. Quenching diameter, D_q, is expected to be proportional to the flame thickness, δ_f. This leads to a Peclet number value at quenching, $Pe_q = D_q/\delta_f$, typically predicted to be of the order of 10 [14–16]. The 1-D thermal approach predicts the right length scale for quenching distance, on the order of a millimeter for hydrocarbon flames [17]. Quenching distance measurements of various mixtures are typically reported at room temperature [17].

* Corresponding author.
E-mail address: jeff.bergthorson@mcgill.ca (J.M. Bergthorson).

http://dx.doi.org/10.1016/j.combustflame.2016.07.030

When the fluid and wall temperatures are raised, the temperature dependent burning rates increase [18], allowing a reduction in quenching distance [18,19]. It is therefore possible to obtain flames in tubes smaller than the conventional quenching diameter at elevated temperatures [18–20]. Detailed numerical and experimental studies on flame quenching in ducts have reported additional phenomena, such as multiple flame shapes [14,21–23], partial quenching near the wall [15,24], radical quenching [19,25], and an influence of flow field on quenching distance [22,24].

In studies investigating the quenching of conventional flames, it is assumed that the wall temperature stays unchanged. However, when the flame propagation velocity is made small, through a change in inflow velocity for example, the wall temperature can become significantly influenced by the flame heat release. This leads to heat-recirculation-dominated flame regimes, associated with slow flame propagation inside narrow tubes [26–32]. In order to model the dynamics and quenching limits of this system involving thermal coupling between the flame and the wall, temperature of the conducting wall needs to be resolved in addition to the fluid temperature field.

Previous studies have investigated the dynamics of flames in various configurations of heat-recirculating burners [29,31,33–39]. These burners allow for a large range of firing rates with flame speeds that can be more than ten times greater than the laminar flame speed predicted from inlet conditions [33,38]. Heat loss is seen to reduce the range of permissible flow rates [35,39]. At the low-end of this range, flames are subjected to an extinction-type limit, where bulk flame temperatures are reduced down to a point where heat release rates become too small to overcome heat loss [35,36]. At the high-end of this range, flames are subjected to a blowout limit [33], where residence times inside the preheat zone become too small for the flame to stay coupled to the wall thermal profile [36].

Norton and Vlachos [36] have specifically investigated the influence of external heat loss on flames in small heat-recirculating channels using a 2-D elliptic model with conjugate heat transfer. It is found that there exists an optimum wall thermal conductivity maximizing burner stability; burner stability refers to the range of permissible values of external heat transfer coefficient. Channels of small width are more likely to sustain an extinction-type limit, while larger channels are more prone to a blowout-type limit. In a subsequent study by the same group [40], a 1-D model is used to evaluate burner stability over a wide range of channel widths. An optimal gap width, at which burner stability is maximized, is found for a particular set of conditions. However, in the 1-D model formulation used in that study, the flame structure is assumed to be flat, such that changes in flame shape are not captured.

In our previous study on heat-recirculating flames in narrow tubes [32], changes in flame shape are observed to become significant when tube diameter and inflow velocity are increased. This leads to highly curved flames for which heat recirculation is significantly reduced, and where burning rate enhancement is mainly associated with an increase in flame burning area [32]. Flame-normal burning velocity at the surface of elongated flames remains close to the laminar burning velocity. Since these elongated excess-enthalpy flames have only been investigated at adiabatic conditions [32], or over a restricted range of conditions [36,41], the impact of external heat loss is still unclear.

In this study, a two-dimensional model for reacting flow with conjugate heat transfer is used to accurately simulate the slow propagation of excess-enthalpy flames in narrow tubes, over a range of tube diameters spanning the micro- and the meso-scale. Heat loss conditions are varied in order to assess their influence on propagation of thermally-coupled flames, and to determine limits of operation. One-dimensional model predictions, which are typically used to model the behavior of this type of system

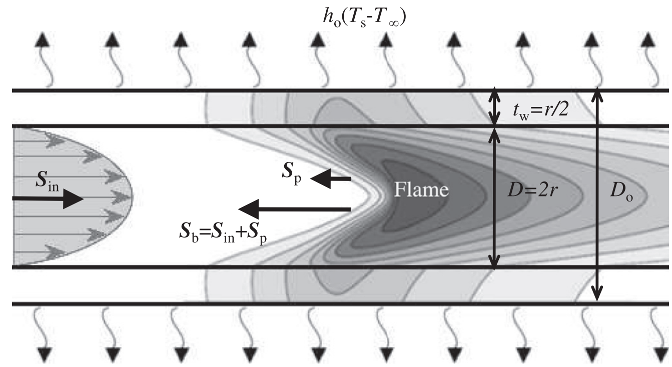

Fig. 1. System of interest: tube of circular cross-section of inner diameter D, outer diameter D_o, and wall thickness t_w, in which a flame propagates. The external tube wall is subjected to convective heat loss to the surroundings. The incoming flow field is a fully-developed parabolic velocity profile of mean velocity S_{in}. The flame propagates at a speed S_p, and the burning velocity is denoted as S_b. Typical temperature contours are shown in shades of gray.

[18,28,29,31,42,43], are used as an hypothesis for the trends to be observed in the study. Qualitative discrepancies in model predictions are used to assess the influence of two-dimensional flame structure effects on the behavior of the system. Flame characteristics are examined to determine the mechanisms leading to heat loss limits in the system.

While heat loss is typically considered to be detrimental, leading to a reduction in available heat at the burner exit [37], this study considers heat loss as a useful phenomenon that allows high-temperature heat transfer to a heat load. This study aims at determining the maximum heat loading an excess-enthalpy flame can sustain, and to help determine which tube diameter is most advantageous for heat transfer to an external heat load; tube diameter being a critical parameter to be determined in the design of an efficient burner for power production. Only stable, strongly-burning flames are considered in this study as they provide the highest power density for power production.

2. Numerical formulation

The system of interest, shown in Fig. 1, consists of a tube of circular cross-section of finite wall thickness in which a flame propagates. This system is the same as the one used in [32], with the difference that the external tube surface is not adiabatic, but subjected to a convective heat loss to the surroundings. This simple geometry can be considered as a fundamental case that extends the classical study of flame quenching inside tubes to a system where heat recirculation occurs inside the tube wall. This study focuses on strongly-burning heat-recirculating flames [32] for which a typical temperature field is shown in shades of gray. The inflow velocity, referred to as S_{in}, corresponds to the mean velocity of the fully-developed parabolic velocity profile that exists upstream of the flame. S_p refers to the flame propagation velocity, which is expected to be small in the slowly propagating flame regime. S_p is positive when the flame is travelling upstream, and is negative when the flame is moving downstream. Burning velocity of the flame is denoted as S_b, and is the sum of inlet and propagation velocities. In this study, the ratio between wall thickness, t_w, and tube inner diameter, D, is kept constant, as shown in Fig. 1.

2.1. One-dimensional asymptotic model

While burning properties of conventional flames are influenced by flow conditions and heat loss conditions, heat-recirculating flames are also dependent on wall properties. This makes the parametric space of the problem larger than for a conventional laminar