Simultaneous measurement of the adiabatic flame velocity and overall activation energy using a flat flame burner and a flame asymptotic model

Roberto Wolf Francisco Jr.*, Amir Antônio Martins Oliveira

Mechanical Engineering Department, Federal University of Santa Catarina, Florianópolis, SC, Brazil

A B S T R A C T

This work presents a method for the simultaneous measurement of the adiabatic flame velocity and the overall apparent activation energy from measurements taken at a single unburned gas temperature. This is achieved using a McKenna flat flame burner and measuring the heat loss from the flame region for different mixture flow velocities. Then, the measurements of laminar flame velocity in the presence of heat loss are curve-fitted to a flame asymptotic model assuming one-step reaction, providing the estimated adiabatic flame velocity and the corresponding overall activation energy. Care is taken to establish clear cut conditions to reduce the effect of flame instabilities in the measurements. Then, an orthogonal regression method is used for the curve fitting and to precisely assess the uncertainties in the adiabatic flame velocity and overall activation energy. The method was tested with mixtures of methane and air, for equivalence ratio between 0.75 and 1.05, 298 K, 1 bar. The values of adiabatic flame velocity and apparent overall activation energy obtained at stoichiometric mixture were 37.8 ± 0.4 cm/s and 271 ± 4 kJ/mol, respectively, which are in good agreement with values from the literature, including estimates using GRIMech 3.0.

1. Introduction

The laminar flame velocity is an integral property of reactant mixtures that combines different physical and chemical phenomena in a single global parameter. It is useful as a design parameter accounting for the characteristic chemical time scale in typical premixed-flame behavior in combustion system, such as ignition, anchoring, flash-back, and relight in turbulent flames [1,2], as well as, a global target for the reduction of chemical reaction mechanisms.

Different methods, such as the Bunsen, heat flux, counter-flow burners and the constant volume reactor are used to measured the laminar flame velocity of fuel mixtures [3–7]. The overall activation energy, in the context of one-step kinetics models, is also an integral property of combustion mixtures assessing the overall effect of temperature in the flame heat release rate. One-step models are useful when combustion is primarily dependent on the diffusion of heat and fuel such that the details of the reaction front are not determinant on how the flame will behave and the only important factor is to account for a thermally sensitive heat release rate in the form of a one-step reaction model [8,9].

In this context, the overall reaction order is useful as a parameter to compare combustion reactivity of different mixtures [10] in chemical kinetics studies [11], and to feed simple reaction models useful in asymptotic analysis [12] and numerical simulations of combustion in complex phenomena, such as HCCI and ramjet engines, turbulent spray, and swirl gas combustors [13–16]. The overall activation energy can also be measured using the same techniques for flame velocity, but it is necessary to preheat the unreacted flow at different temperatures and measure the laminar flame velocity for each temperature. Then, the overall activation energy is obtained through a linear extrapolation of the results, as shown, for example, in [17]. Nevertheless, it is very difficult to measure this parameter with accuracy and the values presented by researchers are accompanied by large discrepancies due to the linear extrapolation applied in the methods [17,18].

The main objective of this work is to revisit the application of the flat burner for the measurement of laminar flame velocity and to present a method for the simultaneous estimation of the adiabatic flame velocity and overall activation energy from a single set of experiments performed at constant reactant mixture temperature, pressure and equivalence ratio using a flame asymptotic model for a single-step reaction. The method relies on the large activation energy asymptotic model for the laminar flame velocity [19,20] and determines the adiabatic flame velocity and overall activation energy from the non-linear curve fitting of measurements obtained at different mixture flow rates. The method establishes clear cut conditions to reduce the effect of flame instabilities in the measurements. Then, an orthogonal regression

---

* Corresponding author at: Mechanical Engineering Department, Santa Catarina State University, Joinville, SC, Brazil.
 E-mail addresses: roberto.francisco@udesc.br (R.W. Francisco), amir.oliveira@gmail.com (A.A.M. Oliveira).

Nomenclature

A	pre-exponential factor [m³/(kg·s)]
A_q	surface area of the burner [m²]
$c_{p,g}$	average specific heat of the reactant mixture [J/(kg K)]
C_w	ratio of the water flow and the gas mixture heat capacity rates
$D_{m,c}$	mass diffusivity of the fuel [m²/s]
$D_{T,g}$	thermal diffusivity of the reactants [m²/s]
E_a	overall apparent activation energy [kJ/mol]
f	non-dimensional flame velocity
h_v	volumetric porous media surface convection coefficient [W/(m² K)]
h_a	enthalpy of air at T_{go} [W/(m² K)]
h_f	enthalpy of fuel at T_{go} [W/(m² K)]
h_p	enthalpy of combustion products at T_r [W/(m² K)]
h_w	average surface convection coefficient in the water flow [W/m² K]
Le_f	fuel Lewis number
L_t	flame stand-off distance [m]
L_s	thickness of the porous plate [m]
$\dot{m}_a$	mass flow rate of air [kg/s]
$\dot{m}_f$	mass flow rate of fuel [kg/s]
$\dot{m}_g$	mass flow rate of reactants [kg/s]
$\dot{m}_w$	water mass flow rate [kg/s]
N_g	number of transfer units from the solid matrix to the gas mixture
N_w	number of transfer units from the solid matrix to the water flow
P	pressure [bar]
P_{sw}	perimeter of the water tube [m]
Pe	non-dimensional stand-off distance
Q	non-dimensional heat transfer flux from the solid matrix to the water
Q_s	non-dimensional heat transfer flux from the solid matrix to the gas mixture
q_k	flame transfer heat to the solid matrix surface [W]
q_{sg}	solid matrix transfers heat to the reactant [W]
$q_{sw} = q_w$	solid matrix transfers heat to the cooling water [W]
R	gas constant [J/(kg K)]
S_L	laminar flame velocity with heat loss (non-adiabatic) [m/s]
$S_{L,o}$	adiabatic laminar flame velocity [m/s]
S_{sg}	specific solid-gas surface area [m²/m³]
T_{go}	reactants temperature at the solid matrix inlet [K]
T_{gu}	reactant temperature in the solid matrix surface [K]
T_r	flame temperature [K]
T_{ro}	adiabatic flame temperature [K]
T_{rm}	average temperature of the flame temperature and the reactant temperature at inlet of the porous plate [K]
T_s	solid matrix temperature [K]
T_{wi}	coolant inlet temperature [K]
T_{wo}	coolant outlet temperature [K]
u_g	mean flow velocity [m/s]
$\dot{V}$	volumetric flow rate [m³/s]
$Y_{O,o}$	unburned mass fraction of oxygen
ε	effectiveness of the heat transfer to the water flow
ϵ	solid matrix porosity
ξ	non-dimensional axial position
η	non-dimensional coordinate along the water tube
θ	non-dimensional temperature
$\emptyset$	equivalence ratio
$\rho_{f,o}$	unburned mass concentration of fuel [kg/m³]
$\rho_{g,o}$	density of the reactant mixture [kg/m³]
λ_g	average thermal conductivity of the gas mixture [W/(m K)]
λ_e	effective thermal conductivity of the porous plate [W/(m K)]

method is used for the curve fitting and to precisely assess the uncertainties in the adiabatic flame velocity and overall activation energy. The McKenna burner was chosen due to its simple operation, low cost, possibility of relatively fast measurements, and wide application in premixed flame and chemical kinetics studies [11,21,22].

2. Modeling and analysis

The simultaneous determination of asymptotic flame velocity and overall activation energy relies on an flame asymptotic model of stabilized flames on a McKenna burner, following [23–26]. Fig. 1 shows a schematic drawing of the McKenna flat flame burner used in this work.

The surface is divided in two concentric porous layers. The inner region receives the reactant mixture that burns stably as a surface flame. The outer region receives a nitrogen flow that acts as a flow curtain shielding the flame from the ambient air. The porous plate is made from sintered metal particles and has a water heat exchanger imbedded in it, that allows for cooling and measurement of the heat transfer rate removed from the flame. The nitrogen curtain increases the flame stability at lower mixture flow rates, but creates and additional heat loss mechanism from the flame. Therefore, the nitrogen curtain was not used in this work and a higher care was taken in the flame stabilization, as it will be shown below.

Fig. 2 presents a rendering of the porous plate with thickness L_s and the expected solid and gas phase temperatures for the burner-stabilized, non-adiabatic, laminar flat flame. The premixed mixture of fuel and air with equivalence ratio $\emptyset$ reaches the inlet face of the porous plate (the lower face) at pressure P, temperature T_{go} and a volumetric flow rate

$\dot{V} = S_L A_q$, where A_q is the surface area of the porous matrix. Following ignition, the flame front stabilizes at a distance L_t from the porous plate surface, named the flame stand-off distance. The stabilization occurs as a result of the heat transfer by conduction q_k from the flame to the surface of the solid matrix, which reaches a temperature $T_s > T_{go}$. Then, the solid matrix transfers heat to the cooling water q_{sw} and to the reactant flow q_{sg} by mechanisms of internal surface convection and radiation heat transfer. The heat transfer to the gas preheats the reactant mixture that then leaves the porous plate at a temperature $T_{gu} > T_{go}$. Since the flame is non-adiabatic, the flame temperature T_r is smaller than the adiabatic flame temperature T_{ro}. The heat transfer rate to the water q_{sw} is estimated from the measurements of the inlet T_{wi} and outlet T_{wo} water temperatures. Therefore, in this experiment, the flame speed
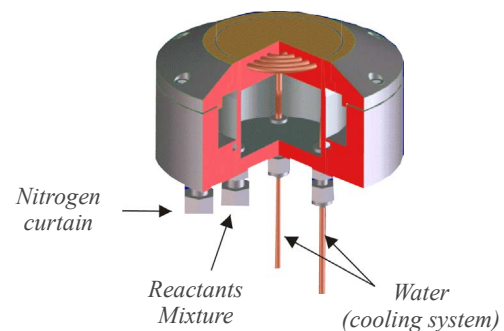

Fig. 1. Schematic drawing of the McKenna burner used in this work (Adapted from Holthuis & Associates, http://flatflame.com/).