INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

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Thesis Title: Investigation on Combustion in Porous Inert Burners Using Gaseous and Liquid Fuels

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SHORT ABSTRACT

Several respiratory and chronic obstructive lung diseases in developing countries have been attributed to the higher levels of indoor pollution. The domestic cooking gas burner is one such device that contributes significantly to this category of emission levels. In India and many other developing countries, the household cooking gas burners use petroleum products like liquefied petroleum gas (LPG) and kerosene as common fuels because their emissions are relatively clean compared to biomass. However, the indoor air pollution has still been of great concern due to the increasing emphasis on more stringent pollution emission requirements. Moreover, considering the increase in demand of LPG and kerosene consumption, as well as depleting fossil fuel conserves, there is a need to not only improve the thermal performances of existing gaseous and liquid fuels fired cooking stoves, but at the same time extensive research is required to check the feasibility and flexibility of burning alternative energy sources in these improved cooking burners. Therefore, towards enhancing the thermal performance and fuel flexibility of existing domestic cooking stoves, the present work employs the heat recirculation mechanism of the porous medium (PM) combustion to these burners offering greater fuel compatibility for both liquefied petroleum gas (LPG) and renewable fuel dimethyl ether (DME). To establish the advantages of DME combustion than that of LPG within the stove, experimental measurements and numerical modeling are performed in a two-layer PM burner. Furthermore, towards extending the applicability of the PM burner to liquid fuel combustion, the flame behavior, soot particulates and other hazardous pollutants of the porous burner integrated kerosene pressure stove are extensively examined for various operating conditions.

SYNOPSIS

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Combustion of gaseous as well as liquid fuels in conventional burners used in thermal devices such as boilers, domestic stoves and furnaces takes place in gaseous environment. Combustion of fuels in the gaseous environment is termed free-flame (FF) combustion. Thermal efficiencies of these devices operating on the FF mode are low, and emissions of CO and NOx are high. Household cooking stove running on liquefied petroleum gas (LPG) or kerosene is one such device that falls into this category.

To meet the requirements of higher thermal efficiency and reduced emissions, over last two decades, many studies have been made to improve the existing LPG and kerosene cooking stoves. In this regard, some researchers have extended the use of porous inert burner (PIB) to the cooking stoves to recirculates the lost heat from burned hot combustion products towards unburned incoming fuel-air mixtures. To further improve the performance of these stoves, two-layered PIB has been used by many researchers. The CO and NOx emissions are significantly low in the two-layered PIB than the conventional cooking stoves, and the thermal efficiency is also higher.

A critical review of previous literature reveals that the experimental investigations of the PIB-based cooking stoves reported in various studies were not guided by numerical analysis, and therefore, studies needed extensive experimental trials for stable combustion in the PIB. Thus, towards improving the performance of the PIB integrated cooking stove, computational modeling for combustion of the fuel-air mixture in these burners is required, which potentially lead to develop more effective burners. The proposed work is, therefore, to develop a numerical tool and validate the solver considering detailed multistep mechanisms with the experimentally measured results. In addition, based on the analysis of experimental data and numerical predictions, the most appropriate burner considering various burner thickness, equivalence ratios, thermal efficiency and CO emissions with respect to the World Health Organization (WHO) emission standard limits is proposed in this thesis.

The present work aims at the numerical and experimental analyses of the combustion of gaseous and liquid fuels inside the PIB. The experiments are performed in a two-layer PIB comprising of silicon carbide (SiC) matrix and aluminum oxide (Al_2O_3) balls. Towards validation of the developed solver, the numerical model is compared to the experimental data from the present work. Volumetric radiative source term in the form of the divergence of radiative heat flux is accounted in the solid phase energy equation. With divergence of radiative heat flux calculated using the finite volume method (FVM), the coupled continuity, species conservation equation, ideal gas equation, energy equations for gas and solid phases are solved using the finite difference method. Species production rates, equation of state variables, transport and thermodynamic properties are calculated using open source software Cantera.

Because of increasing concern about stringent emission requirements and energy conservation, in recent years many researchers have paid significant attention to alternative fuels. As a promising renewable energy source, dimethyl ether (DME) is known as a leading alternative fuel additive. However, when DME is used in the conventional burners, difficulties associated with flame sustainability and low flammability limit arises due to its lower calorific value. Therefore, towards enhancing the fuel flexibility of the existing domestic stoves, the present work utilizes the heat recirculation mechanism of the PIB to these burners offering greater fuel compatibility for both LPG and DME. Furthermore, to analyze the complex kinetics and reaction pathways of LPG/DME combustion inside the burner, a comprehensive modeling of the PIB is studied through a detailed kinetic mechanism. The reaction pathway studies are performed using an extended kinetic model developed by adding various sub mechanisms taken from literature.

The results of the present work are of great importance, not only for providing high efficient and low emission burner fully compatible for both DME and LPG, but also for providing a solution to the limitations and challenges faced by current DME stove market. In the present work, it has been found that with the addition of DME in the LPG-air mixture the peak radical pool concentration increases, which enhances the filtration velocity and thus the operating limit of the PIB. Moreover, with the use of DME instead of LPG, following the guideline of WHO, the maximum allowable equivalence ratio can be extended from 0.4 to 0.5 and the thermal load from 4.0 kW to 5.0 kW. Towards reducing the dependence on the petroleum product LPG, the results from the present study show excellent performance of the PIB-based stove with an improvement in radiant efficiency as well as a reduction in CO emission by the use of DME instead of LPG.

Despite the substantial research on the porous media combustion (PMC) involving both experimental and numerical investigations, to date, there is no study available in the literature addressing the formation and growth process of soot aerosols within the PIB. Thus, in this thesis, the effect of PMC on the formation of soot and its components inside the PIB is examined. The formation of soot due to the combustion of the fuel-rich ethylene-air mixture inside the PIB is assessed by using a detailed soot mechanism based on discrete sectional method (DSM). The results in this work show that the PIB not only reduces the CO emission but also can suppress the soot formation and delay the particle inception as compared to the premixed laminar FF combustion. The soot volume fractions at the PIB exit are predicted to be in the range of 10^{-12} - 1.5×10^{-7} which is very much lower than that of FF (10^{-7} - 10^{-6}) under all the input conditions examined in this study. In case of PIB, the maximum soot particle diameter is found to be 20 nm smaller than those formed in the FF condition. A brief discussion of the Chapter wise details of this Ph.D. thesis is provided below:

The present thesis contains 8 Chapters. The introductory Chapter provides a literature survey about the state-of-the-art of the PIB technology. Working principle and importance of the PMC for various application are discussed. Following the analysis of the available literature, the motivation and objectives of the present doctoral study are discussed for the research work.

The present study is an effort towards the feasibility of employing the concept of PIB in the domestic cooking burners. In order to study the complex combustion process inside the PIB, the complete non-equilibrium model to solve the macroscopic transport equations is presented in Chapter 2. The basic mathematical formulation and solution

procedure for solving the quasi-steady radiative transfer equation for the volumetric radiation source term of the porous medium using FVM are also described in detail. To compare the advantage of gaseous fuel combustion in the PIB over its combustion in the FF mode, in terms of both heat output and emissions, multistep chemical kinetics and detailed reaction mechanism are considered.

The third Chapter of the thesis reports the numerical and experimental analyses of LPG combustion within a two-layer PIB-based cooking stove. Numerical results of temperature distributions, flammability limits and pollutant emissions for various equivalence ratios and thermal loads are found to have a good agreement with the experimental data. Towards improving the thermal performance of the stove, effects of burner thickness, preheater thickness, solid-phase conductivity and scattering albedo on CO emissions and radiative flux are also studied.

To establish the applicability of DME as an alternative fuel additive to LPG for enhancing combustion and reducing hazardous emissions, in Chapter 4, the flame behavior of LPG-air mixture blended with DME is studied within the PIB under excess enthalpy combustion condition. New filtration velocity data are found for the stable combustion of LPG-DME-air mixtures inside the PIB. The effect of various DME volume fractions in the LPG-DME blends on temperature distribution, radical pool concentration, reaction zone thickness and syngas production are investigated. In Chapter 5, the performance of the DME fired PIB in terms of radiative efficiency, CO emissions and stable operating ranges for various input conditions are compared with the results for LPG combustion. Furthermore, the numerical model is used to investigate the dynamics of DME flame in the PIB through reaction path analyses.

Chapter 6 investigates the effect of PMC on the sooting behavior of premixed fuel-rich ethylene-air flame inside the PIB. In an effort to elucidate soot evolution processes, a DSM based soot kinetic mechanism comprising of 156 chemical species and 5600 reactions is used. Chapter 7 deals with the investigation of combustion of kerosene in a PIB integrated pressure cooking stove. The results show that with the incorporation of the porous matrix in the kerosene pressure stove, soot emissions go drastically down. Finally, the conclusions and recommendations of the future work are outlined in Chapter 8.