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Influence of the air inlet ports on the inverse diffusion flame characteristics.

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STATEMEN

This dissertation is submitted to Ain-Shams University for the M.Sc degree in Mechanical Power Engineering Department.
The work included in this thesis was carried out by the author in the Mechanical Power Engineering Department, Ain Shams University.
No part of this thesis has been submitted for a degree or a qualification at any other university or institute.

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ABSTRACT

The present work concerned with microstructure and macrostructure of the inverse diffusion flames produced by different design parameters and aerodynamic variables. An experimental study was devoted to enhance the combustion performance and heat transfer rates from inverse diffusion flames as stabilized on a burner that has a central air jet surrounded by an array of fuel jets. The investigation was performed to explore the effects of changing the inlet air port and the fuel ports' geometry on the flame thermal structure and the exhaust emissions. In this regard, the features of the circumferentially arranged ports (CAP) were examined where a wide range of velocity and momentum flux ratios was included. Five inverse diffusion flame burners with different air jet ports (of diameters namely 4, 6, and 8 mm) were tested. The 4 mm jet diameter burner was designed with two different center to center distances of 12 and 15 mm. A case was used with circumferentially distributed air ports. Such arrangement of the air ports highlighted the influence of increasing the number of the air ports on the resultant flame features. The fuel flow rate was kept constant while the air flow rate was varied to cover a wide range of the central air Reynolds numbers with a corresponding range of the primary equivalence ratio.

The experiments carried out were divided into four phases. The first part concerned with the experimental determination of the stability limits of each burner. The second part concerned with the investigation of the visual characteristics of the inverse diffusion flames, the illumination of the different reaction zones in addition to the indication of the flame height. The third part concerned with the investigation of the flame structure, including the flame temperature distribution and the exhaust species concentration. The final part dealt with measuring the heat flux during the flame impingement.

The results showed that the burner of the smaller d_{air} produced stable bluish flame in wide ranges of Re_{air} and Φ_p due to the turbulence induced in the flame neck and the stronger entrainment of the surrounding air in the post-flame region. The smaller d_{air} also produced higher T_f in excess of $1700^{o}C$. An enhancement occurred with using the new design of distributed air ports. The centerline flame temperature and the heat flux variation increased. A reduction in the pollutant emissions was obtained. The mixing zone was characterized by the rapid change of the concentrations and the rapid increase in T_f. The CO was efficiently converted into CO_2 in the post-flame reaction zone in the presence of the entrained air. The smaller d_{air} reduced the NOx emissions due to the role of turbulence and the suppression of the prompt NOx formation. Concerning the flame impingement onto a flat plate, using smaller air diameters and a number of air jets produced higher levels of heat flux, where the combustion was more efficient than that of the port normal design. As the fuel lean mixture conditions were approached, the flame heat flux variation at any flame height decreases with increasing the air jet Reynolds number Re_{air}. Upon decreasing the center to center distance, the centerline temperature showed higher temperatures. Smaller air diameters in the distributed air ports' design were associated with higher peak flame temperatures and wider ranges of flame stability.

Increasing the air jet Reynolds number by 30% increased the peak flame temperature by 8.3%. In the primary equivalence ratio range between 0.8 and 2.0, the impingement plate optimum spacing for the maximum heat flux was found to correlate well with Reynolds number. The flame color changed from bluish to yellowish upon switching from the burners of smaller diameters to the burners of larger diameters. The same qualitative features were obtained as the number of the fuel ports increased. The results proved that the nature of the flames issuing from the distributed jets' burners involving inverse diffusion flames is determined by the combined effect of the burner geometry and the jet aerodynamics. The air Reynolds number and the primary equivalence ratio, Φ_p, may be used to describe the performance of a particular burner of invariable geometric parameters. In addition, the burner performance under any conditions of air Reynolds number and primary equivalence ratio cannot be used to predict the performance of another burner unless the conditions of geometric and dynamic similarities are satisfied.

CONTENTS

CHAPTER 1
INTRODUCTION

Most of the practical combustion systems such as gas turbine engines and rocket combustors employ non-premixed combustion due to its higher flame stability limits, safety, and wide operating range in comparison to the premixed combustion. Non premixed flames correspond to situations where the fuel and the air, are not initially mixed and originate from two separate streams. Under such circumstances the fuel/air mixing takes place simultaneously with combustion that proceeds at the stoichiometric conditions. However, the presence of soot in non-premixed combustion burners has an undesirable effect on the practical combustors. Regarding another important aspects these carbon particles cause potential threat to the human health and environment.

There are two kinds of non premixed flame arrangements according to how the fuel and the air steams are introduced into the burners. These include Inverse diffusion flames (IDFs) and normal diffusion flames (NDFs). The Inverse diffusion flames (IDFs) are similar to normal diffusion flames (NDFs), except that the relative positions of the fuel and oxidizer are exchanged. The Inverse Diffusion Flames (IDFs) were observed to produce less soot as compared to Normal Diffusion Flames (NDF). Recently, there has been a growing interest among researchers in IDF.

The Inverse Diffusion Flame can be observed in a simple coaxial burner configuration when high velocity air jet surrounded by low velocity annular fuel jet is ignited. One of the applications of inverse diffusion flame is in impingement heating because premixed flame burners are rarely used in industrial purposes for safety reasons. Direct gas flame impingement is employed in a wide range of industrial and domestic heating. There has been continued effort in the investigation of the thermal characteristics of the flame continuous impingement systems. Part of investigations is devoted to determine the emissions from (IDFs). The thermal performance of a flame impingement system is dependent significantly on four factors: the burner style, the flame jet properties, the impingement surface condition, and the configuration between the burner nozzle and the surface, [30]. The flammability range of premixed flame burners is small and the effective heating area is relatively small with high peak heat flux. On the other hand, impinging diffusion flame burners with high Reynolds numbers have long been used in industrial furnaces but the formation of soot is an associated problem.

Premixed gas-fired flame dominates the domestic and commercial applications because of its rapid and clean combustion characteristics, but it has significant drawbacks of low heat utilization rate, low flame temperature, and stability problems at low port loading operation condition. Thus, full utilization of premixed gas-fired flames is usually restricted by its narrow flammable limits and hence the range of stability.

The advantages of inverse diffusion flames (IDFs) and their potential domestic and industrial applications have motivated the continual of the studies. Because IDFs are able to exploit the advantages of both diffusion and premixed flames, in regard to operational safety, acceptable pollutant emission levels, and flame stability. The feasibility of applying IDFs in industrial and domestic heating processes became of interest. The research works cover the area from the investigation of the flow and the flame structure, the flame stability, the flame temperature and the pollutant emissions of open IDFs, to the heat transfer characteristics of impinging IDFs. The inside limits of the relative momentum between air and fuel jets ensure better fuel entrainment and enhanced mixing in IDF configuration as compared to NDF. As a result, flames with less soot can be established easily in IDF configurations.

Diffusion flames constitute one of the most basic flame configurations in the combustion process. Numerous investigations have already been carried out to gain an understanding of the characteristics of these flames. In the case of the inverse diffusion flames if the air jet velocity is high enough, the fuel at the outer jet(s) due to the high pressure drop and high rate of momentum exchange between the air and the fuel jets, is entrained inward and mixes with the air to form a partially premixed flame. Otherwise, it might burn mainly in the normal diffusion mode. The IDF because of this inverse entrainment and also due to the entrainment of the ambient air surrounding the fuel jets is a combination of a premixed flame and a diffusion flame that can have a larger flammability range than the premixed flame and is cleaner than the diffusion flame.

The combustion process is strongly influenced by the dimensions and shape of the recirculation zone, because it carries hot combustion products and active chemical radicals backwards and supplies energy for ignition of the incoming reactants. However, the combustion phenomena can be significantly affected by many variables such as the burner geometry, the method of swirl generation, the fuel induction geometry, the exit nozzle design, the swirl number, and Reynolds number. Swirl combustion has been extensively used in various engineering devices. Swirl due the better fuel-air mixing which it produces an effective aerodynamic means to stabilize the flame, control the combustion process, enhance the heat and mass transfer, and increase the combustion efficiency. The benefits of swirl combustion depend in most instances on the formation of a toroidal recirculation zone which allows flame stabilization and better fuel-air mixing to occur in regions of relative low velocity where the flow velocity and the flame speed can be matched, aided by the recirculation of heat and active chemical species. When the central air jet velocity is low, the fuel jet will be in contact with the air at the inner side forming a bell shaped blue or yellow flame depending upon how much low it is, while at the outer surface of the fuel jets it forms an annulus diffusion flame. However when the central air jet velocity is high enough, the fuel jet will be entrained towards the central air jet. The entrained fuel mixes with the air to form a partially premixed flame.

These features make the use of the inverse diffusion flame burners desirable and are becoming of growing interest in industrial heating processes, but few studies have been performed using the inverse diffusion flame configuration compared to the normal diffusion flames literatures. This work is concerned with the study of the characteristics of the inverse diffusion flames obtained using circumferential arranged fuel ports around the central air jet. The influence of the number of the fuel jets, the radius of their pitch circle around center of the air port, the fuel ports center to center distances, the variation of the air jet Reynolds number and consequently the equivalence ratio, while keeping both of the total fuel flow rate and the fuel jets velocity unchanged, on the inverse diffusion flame characteristics including the flame type, color, structure, temperature, emission of pollutants and heating flux. In this work also is concerned with changing the design of the air inlet ports and its influences on the characteristics of the flame. The entrainment effect depends on the ratio of the air jet momentum and the fuel jet momentum. Therefore by adjusting the air jet velocity or the fuel jet velocity, the flame configuration changes from a diffusion flame to a premixed flame and a flame with characteristics in between can be produced and controlled.

As the air and fuel supplies are initially separated, even when the fuel is entrained by the central air and burned in premixed mode, part of the fuel might still burn in the non-premixed mode due to either poor mixing or an excessive amount of the fuel. This results in a flame with upstream fuel-lean or stoichiometric combustion and downstream fuel-rich or non-premixed combustion. Such flame nature is similar to the staged combustion adopted for reducing NOx emission through the process of NOx re-burning. In staged combustion, usually a secondary air or fuel supply is needed to provide a secondary combustion in the flue gas zone, [15, 53].

CHAPTER 2
LITERATURE SURVEY

2.1 Introduction

Diffusion flames constitute one of the two basic flame configurations in the combustion process. Numerous investigations have already been carried out to gain understanding of the characteristics of such flames. The inverse diffusion flame (IDF) is a kind of flame with an inner air jet surrounded by an outer fuel jet(s). If the air jet velocity is high enough, the fuel at the outer jet(s) is entrained inward and is mixed with the air to form a partially premixed flame (otherwise, it may burn mainly in the diffusion mode). The IDF in this case becomes a combination of a premixed flame and a diffusion flame that has a larger flammability range than that of the premixed flame, while combustion becomes more efficient in comparison to the diffusion flame. Therefore, the feasibility of applying IDFs in industrial- and domestic-heating processes is of interest.

2.2 Diffusion Flame Basic Theory and characteristics

Burke and Schuman, [1], investigated the structure of enclosed cylindrical diffusion flames. Two general flame shapes were identified: (a) a conical flame surface converging towards the tube axis, called an "over ventilated" flame; (b) an upside down cone shape, called "under-ventilated" flame. The term "diffusion" describes the mechanism where the oxidizer diffuses into the fuel stream causing simultaneous mixing and combustion. The rate of combustion depends on the rate of mixing between the oxidizer and the fuel rather than the much faster chemical reaction rate. When