旋转、逆转火焰的热特性

和污染排放特性

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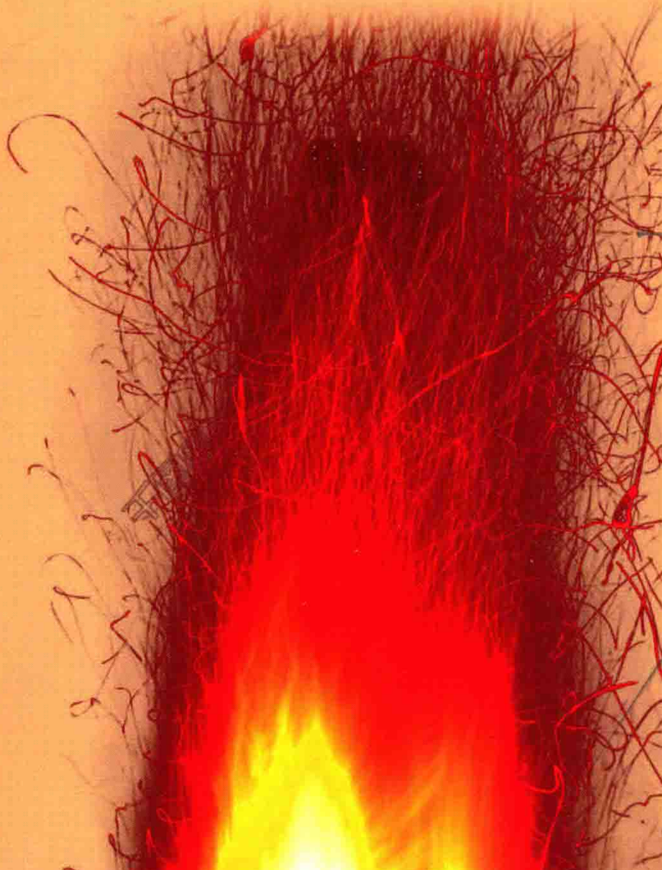
甄海生　著



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内 容 提 要

本书旨在研究以液化石油气（LPG）为燃料的一种基于旋流的、超稳定燃烧的逆转扩散火焰（IDF）的热、污染和传热特性，主要以实验性质为主。第1章为概况和动机；第2章是研究的背景，其中包含与逆扩散火焰相关的前期工作的详细文献回顾；第3章介绍了实验装置、仪器和测量方法；第4章到第7章，分别介绍火焰外观、火焰结构、火焰温度场、火焰稳定气体种类、火焰冲击热传递、火焰比较等；第8章是旋转火焰的数值模拟，计算结果作为实验研究的补充；最后，在第9章中对本书的研究结果和结论进行了全面的讨论，并对今后的工作提出了建议。

本书是研究旋转、逆转火焰的学术类专著，具有较高的学术价值，对于专门从事研究旋转、逆转火焰的科研人员及学术类研究群体具有非凡意义。

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甄海生，男，1979年出生于河北省，吉林大学学士，哈尔滨工业大学硕士，香港理工大学博士。2006年赴香港从师Leung Chun Wah、Cheung Chun Shun教授，研究火焰燃烧热特征，污染物排放及冲击换热10余年。研究对象和内容涵盖预混、非预混，层流、湍流，旋流、非旋流，富氧、贫氧和富氢火焰；传统石化燃料和可再生新燃料；火焰燃烧的热释放、污染物产成机理和控制，洁净燃烧和节能减排技术；火焰热释放和热能高效利用；以及燃烧噪音机理和防治。

前 言

本书旨在研究以液化石油气（LPG）为燃料的一种基于旋流的、超稳定燃烧的逆转扩散火焰（IDF）的热、污染和传热特性。开发的旋流燃烧器可产生高度旋转 IDF，其几何涡旋数高达 9.12，且火焰内部形成回流。旋转 IDF 的控制参数有射流雷诺数 *Re*，化学总当量比 *Φ*，几何涡旋数 *S′* 和喷嘴到目标距离 *H/d*。本课题用实验方法研究旋转 IDF 的火焰特征，包括火焰外观、火焰结构、火焰温度、火焰内气态物质、火焰总体污染物排放和火焰冲击传热。

旋转 IDF 外形像桃子。火焰结构分析将其分为三个特征区域。区域 1 是中心位置的回流区（IRZ），它靠近燃烧器出口。IRZ 回流区是由旋转射流中轴向逆压梯度引致，其体积占到火焰总体积主体。区域 2 是靠近下部的火焰边界区域，该区域一方面与外侧环境空气接触，另一方面在内侧与区域 1 接触。3 区则是靠近上部的火焰边界区域。IRZ 的 1 区通过具有逆向回流而与其他两个区域不同。在涡流旋转作用下，从燃烧器出来的流体颗粒依次通过区域 2 和区域 3，然后区域 3 中大部分流体颗粒逆转流动方向发生回流，流向燃烧器轴线及出口，形成 IRZ 的 1 区。因此，区域 3 可作为 IRZ 回流流体颗粒来源区域。

温度和火焰内部 O_2/CO/CO_2/NOx 浓度测量表明，这些参数的分布与流场耦合。可以看出，区域 1 是大体积、高温的 IRZ。由燃烧器供应的空气 / 燃料、燃烧产物和夹带的环境空气之间发生强烈混合，从而导致温度和气态物质浓度分布均匀。区域 2 在温度和气态物质浓度方面均具有明显梯度，这是因为在这个小体积区域内流场参数发生迅速变化。区域 2 颜色维持在海军蓝色不变，这是因供应的空气 / 燃料在这里发生强烈混合并同时发生强烈燃烧，这也表明该区域是火焰前沿面。区域 3 是后燃烧区，内部发生着燃烧产物的氧化、积聚和稀释，并且经过前两个区域后未烧尽的燃料在这里扩散燃烧。从 *Re* 和 *Φ* 对火焰内部气态物质浓度的影响可以看出，浓度分布与燃烧条件紧密耦合。其中，CO_2 和 NO_x 浓度具有与火焰温度相似的变化趋势，所以因热生成 NO 的机制会主导 NO_x 形成。从尾气测量中获得

的数据显示，在某些燃烧条件下，中等水平 NO_x 排放和超低 CO 排放水平可以共存。

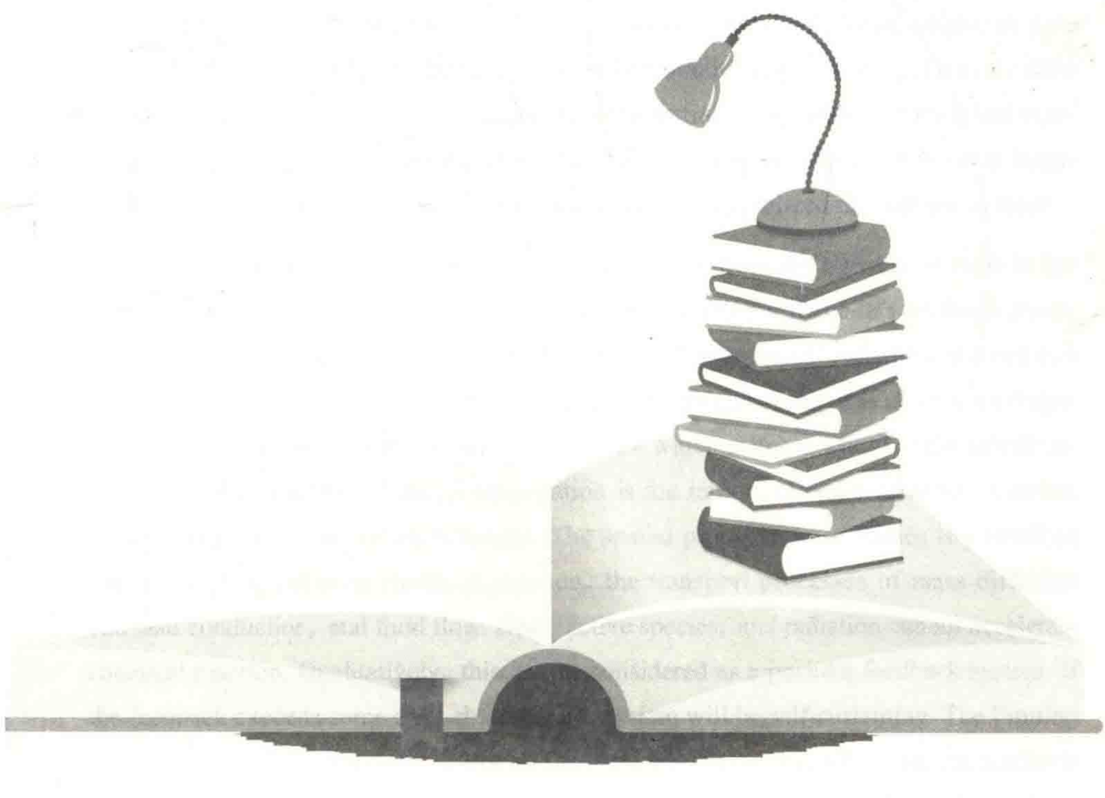
当旋转 IDF 向上垂直冲击到平坦表面时，旋转效应以三种方式影响局部热通量：1. 停滞点处的热传递被严重抑制；2. 局部热通量峰值发生在远离停滞点一定径向距离处；3. 局部热通量峰值的径向位置随着 H（喷嘴 – 目标距离）增加而更加偏离停滞点。存在一个最佳 H 值使得目标表面的热传递达到最大值，并且该最佳 H 在雷诺数和涡旋数不变时随着 Φ 增加而增加。

对旋转 IDF 与相同工况下非旋转 IDF 比较发现，旋转 IDF 火焰长度更短、更稳定。还发现，旋转 IDF 中 IRZ 的存在对火焰稳定性提高和长度缩短起到非常重要作用。相比于非旋转 IDF，由于有更强烈混合和更充分燃烧，旋转 IDF 在本质上是部分预混合火焰，因此它更清洁，烟灰形成较少。此外，旋转 IDF 较非旋转 IDF 产生略高 NOx 排放指数（EINOx）和更低的 CO 排放指数（EICO）。冲击热传递的比较表明，在非旋转 IDF 中产生冷核的小 H 位置旋转 IDF 具有更充分的燃烧，从而具有更高的传热速率。然而，旋转 IDF 在较高 H 处具有较低的热传递速率，而非旋转 IDF 此时能获得较充分燃烧从而具有较高热传递速率。这是因为在高 H 时旋转 IDF 火焰已经被夹带的环境空气充分冷却了。通过在相同的 Re 和 Φ、以及它们各自最佳 H 时比较旋转和非旋转 IDF，结果发现涡旋流对火焰总体热传递有负面影响。

在相同供气和送风条件下，比较了两种不同的燃气 / 空气混合机制，即预混（PMF）火焰和扩散（IDF）火焰。结果表明，两种旋转火焰具有相似视觉特征，包括火焰形状，尺寸和结构。这是因为作为影响旋转射流空气动力特性的重要参数：雷诺数和涡旋强度在两种火焰中几乎相同。PMF 和 IDF 两种火焰均被 IRZ 提升了稳定性，同时 IDF 的稳定性高于 PMF。这证实了 IDF 是预混火焰和扩散火焰的组合，并可以拥有两种火焰的优点。两种火焰中由燃烧器供应的空气 / 燃料、燃烧产物和夹带的环境空气之间保持了良好的混合，使得 IRZ 内气态物质包括 O_2、CO、CO_2 和 NO_x 在内的气体成分和温度分布均匀。与 IDF 比较，PMF 可获得较低水平的 NOx 和 CO 排放。在 PMF 中，燃料和空气的预混合显著增强了未燃混合物各向均匀性，并降低了燃烧区内燃烧生成物的停滞时间，从而降低了 NO_x 形成。此外，由贫燃燃烧产生的低温也有助于减少通过 NO 热机制形成的 NO_x 数量。PMF 具有较低 IDF, EICO 是由于燃料和空气的预混合以及较高的 O_2 浓度，这两个因素都促使 CO 向 CO_2 的转化。

CONTENTS

CHAPTER 1 INTRODUCTION



1.1 Combustion and flame

Combustion is the oldest technology of mankind and has furnished man with a major source of energy for more than one million years and at present, about 90% of our energy support (e.g., in traffic, electrical power generation, heating) is provided by combustion. The advent of nuclear energy has provided a rival energy source to combustion. However, many years will elapse before combustion loses its predominance and for the foreseeable future, it will continue to have important applications both as an energy source and in various industrial processes. Therefore, combustion will continue to be studied by researchers and quantitative understanding of this phenomenon is a desirable practical goal as well as of intrinsic interest.

Webster's Dictionary provides a definition of combustion as "rapid oxidation generating heat, or both light and heat; also, slow oxidation accompanied by relatively little heat and no light." This definition emphasizes the intrinsic importance of chemical reactions to combustion. It also emphasizes why combustion is so useful: combustion transforms energy stored in chemical bonds to heat which can be utilized in a variety of ways.

The objective of combustion is to retrieve energy from the burning of fuels in the most efficient way possible. Combustion can occur in either a flame or non-flame mode. What is a flame and how does it differ from other reacting systems? A flame is defined as a combustion reaction that can propagate subsonically through space. It is usually accompanied by the emission of visible radiation, a feature which is not essential to the definition. However, the property of spatial propagation is the important one which distinguishes flames from other combustion reactions. The spatial propagation of flames is a result of strong coupling between chemical reaction, the transport processes of mass diffusion and heat conduction, and fluid flow. Heat, active species, and radiation can all accelerate chemical reaction. Qualitatively, this can be considered as a positive feedback system. If the feedback exceeds some critical factor, the system will be self-sustaining. The limiting factor is the convection velocity carrying fresh material to the reaction, since the feedback is inversely proportional to it. The existence of flame movement implies that the reaction is confined to a zone which is small. This reaction zone is called the flame front, combustion wave, or combustion zone. We shall use the first designation in this thesis.

Flames are commonly classified according to three broad means: dispersion, aerodynamic flow, and initial physical state. The first of these has to do with the state of mixing of the reactants, or whether the reactants are premixed before entering the reaction zone. This criterion categorizes flames as being either premixed flames or non-premixed (diffusion) flames. In a premixed flame, the fuel and the oxidizer are mixed at the molecular level prior to the occurrence of any significant chemical reaction. Contrarily, in a diffusion flame, the reactants are initially separated, and reaction occurs only at the interface between the fuel and oxidizer, where mixing and reaction both take place. The term "diffusion" applies strictly to the molecular diffusion of chemical species, i.e., fuel molecules diffuse toward the flame from one direction while oxidizer molecules diffuse toward the flame from the opposite direction. In practical devices, both types of flames can be present in various degrees.

The second broad means of classification concerns the nature of the gas flow through the reaction zone in the fluid dynamic sense, i.e., whether it is laminar or turbulent. Laminar or streamlined flow implies that all mixing and transport must be done by molecular processes, while in turbulent flow this is aided by a macroscopic eddying motion. In turbulent non-premixed flames, turbulent convection mixes the fuel and oxidizer together on a macroscopic basis. Molecular mixing at small scales, i.e., molecular diffusion, then completes the mixing process so that chemical reactions can take place.

The third method of classifying flames specifies the initial physical state of the reactants—solid, liquid, or gas. Solid particle flames are probably best typified by those of coal dust in air. Liquid droplet or spray combustion is widely known in common oil burners, jet engines, etc., while gas flames are still more common and are self-explanatory.

These classes of flames—premixed or diffusion; laminar or turbulent; and gaseous, droplet, or particle—suffice as major divisions of flames. Other properties besides these serve to differentiate flames too, and the classification of a flame according to one of these subdivisions has an important bearing on its structure in one way or another, as will now be brought out.

Stationary flames or non-stationary flames

Deflagration or detonation flames

Open or enclosed flames

Normal or inverse flames

Stationary flames are opposed to non-stationary or propagating flames in the sense that the flames are stationary with respect to a reference point. The flame burning velocity is balanced by the flow velocity in a stationary flame. Most industrial flames belong to this category. Flame propagating down a tube filled with combustible mixture is an example of non-stationary flames.

The classification of flames into deflagration or detonation flames refers to the nature of flame burning velocity or flame speed. A deflagration flame propagates at subsonic velocity through gradual heat and mass transfer between the burned and unburned gas. A detonation flame is sustained by a shock wave through the high temperature and pressure rise behind the shock front. The flame front in a detonation flame propagates at super-sonic velocity.

The distinction between open or enclosed flames comes from the combustion system boundaries. Industrial flames usually occur in a vessel or combustion chamber with controlled fuel and air supplies. Such flames are called enclosed flames in contrast to open flames which are formed between a fuel jet and unbounded surrounding atmosphere. Flow patterns differ between an open and an enclosed flame since a vessel represents an impermissible mass boundary which affects fluid flow.

The last classification criterion considers the relative position of the fuel and oxidizer streams. In a normal flame, the fuel jet is surrounded by the oxidant jet. An inverse or reversed, reciprocal flame is defined here as a flame with a central oxidant jet surrounded by a fuel jet. In a broad sense, neither the fuel nor the oxidant needs to be a pure stream in an inverse flame. This criterion will be discussed in the next section.

1.2 Inverse diffusion flame

Inverse diffusion flames can be formed by two concentric tubes, comprising of an inner air jet and an outer fuel jet, under either confined condition or unconfined condition. Confined condition refers to an enclosed flame while an unconfined flame is an open flame in atmosphere. Since fuel and air supplies are initially separated, inverse diffusion flames are non-premixed in nature and the combustion performance is highly dependent on the degree of mixing between the fuel and air. A thin bell-shaped blue reaction zone will be formed at the jet exit under the equilibrium of jet velocity and flame burning velocity. The blue reaction zone is the surface of contact between the fuel and air where stoichiometric combustion takes place. In confined condition, however, it is very difficult to obtain a balance between jet velocity and flame burning velocity. Therefore confined inverse diffusion flames are usually unstable. In unconfined or open condition, fuel and air are injected into atmosphere. An air-fuel-air arrangement is formed, in which the central air jet is surrounded by the annular fuel jet and in turn the fuel jet is surrounded by ambient atmospheric air. When the central air jet velocity is low, the fuel jet will be in contact with the air jet at the inner side forming a bell-shaped blue flame and with the atmospheric air at the outer side forming an annular diffusion flame. When the central air jet velocity is high enough, the fuel jet will be entrained towards the air jet at the inner side and the mixing between the entrained fuel and the central air will produce a partially premixed flame. Even when the fuel is entrained by the central air and burned in premixed mode, part of the fuel may still burn in non-premixed mode due to either poor mixing or an excessive amount of fuel. This can result in a flame with upstream fuel-lean or stoichiometric combustion and downstream fuel-rich or non-premixed combustion. Such a flame configuration is similar to the staged combustion technique adopted for reducing NO_x emission through the process of NO_x-reburning. In staged combustion, usually a secondary air or fuel supply is provided to assist secondary combustion in the flue gas zone. The NO_x formed in the primary combustion zone is converted to HCN and eventually "burned away" in the secondary combustion zone. Inverse diffusion flames at high equivalence ratios will establish exactly similar staged combustion arrangement and therefore have potential application in low NO_x burners.

In recent years, inverse diffusion flames have gained popularity and attracted the attention of many researchers because they exhibit the characteristics between those of premixed and non-premixed flames. Due to the non-premixed nature, diffusion flames have a wide range of flammability even in turbulent state, but with a high soot-loading characteristic which sets a limit to their domestic applications where clean combustion is required. Premixed flames are cleaner and burn more intensely, but with a narrow range of operation due to the occurrence of flash-back and lift-off. With regard to inverse diffusion flames, by separately adjusting the fuel and air supplies, we can control the flame configuration from a premixed flame to a diffusion flame or a flame with characteristics in between.

1.3 Scope and objective of study

As a combination of premixed and diffusion flames, inverse diffusion flames are capable of exploiting the advantages of both premixed flames and diffusion flames, in regards to operational safety, pollutant emission, and flame stability. Specifically, inverse diffusion flames have no flash-back, reduced soot formation, a wide range of operational conditions and flexibility in flame length adjustment, coupled with potential NO_x-reburning capability. These advantages of inverse diffusion flames and their potential industrial and domestic applications have motivated this research work.

Numerous articles have been published dealing with the two basic flame types of premixed flames and diffusion flames, however, in the history of flame research, only a few investigations on inverse diffusion flames have been carried out. Among them, the study of flame structure is the specialized topic of interest to combustion scientists and engineers. Flame structure is the term used in one sense to describe the process taking place within the flame itself and in another sense to describe the external appearance of the flame. Besides flame structure, former investigations are mainly focused on their low soot-loading characteristic. Other concerns include the study of pollutant formation mechanisms and the application of inverse diffusion flames in flame impingement heat transfer.

Energy conservation and environmental concerns emphasize the need for fundamental investigation of the mechanisms of pollutant formation. So both thermal and emission characteristics of swirling inverse diffusion flames are to be investigated in details. This study also aims to better understand the phenomena such as flame extinction, quenching and heat and mass transport properties.

This dissertation aims at investigating and comparing inverse diffusion flames with and without swirl. The introduction of a swirling motion to the inverse diffusion flame is proposed to reduce its flame length. The governing parameters of the inverse diffusion flame with swirl will be fully identified and their effects on flame length, flame stability and preferential separation distance for heat transfer etc. will be investigated. It is the objective of this study to exploit the feasibility of utilizing swirling inverse diffusion flames in flame impingement heat transfer.

We begin our study of swirling inverse diffusion flames by developing a swirl burner and testing its performance. The burner aims to generate flames operating in high swirl mode. Then, detailed investigations go to the followings: