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Emission of impinging swirling and non-swirling inverse diffusion flames

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ABSTRACT

The overall pollutants emission from impinging swirling and non-swirling inverse diffusion flames (IDFs) was evaluated quantitatively by the 'hood' method. The results of in-flame volumetric concentrations of CO and NO_x and overall pollutants emission of CO and NO_x in terms of emission index were reported. The in-flame volumetric concentrations of CO and NO_x were measured through a small hole drilled on the impingement plate. In comparison with the corresponding open flame, the CO and NO_x concentrations for the impinging swirling IDF are greatly lowered due to the entrainment of much more ambient air which is related to the increased flame surface area. For the swirling and non-swirling IDFs, the $EINO_x$ increases as the nozzle-to-plate distance (H) increases because more space is available for the development of the high-temperature zone in the free jet portion of the impinging flame, which favors the thermal NO formation. The variation of EICO with H is different for the impinging swirling and non-swirling IDFs because they have different flame structures. For both flames, the EICO is high when their main reaction zone or inner reaction cone is impinged and quenched by the copper plate. The parameters of air jet Reynolds number, overall equivalence ratio and nozzle-to-plate distance have significant influence on the overall pollutants emission of the impinging swirling and non-swirling IDFs and the comparison shows that the swirling IDF emits less NO_x and CO under most of the experimental conditions tested. Furthermore, it is found that compared with the open flames, the impinging flames emit lower level of NO_x and higher level of CO.

1. Introduction

Direct gas flame impingement is employed in a wide range of industrial and domestic heating or drying processes, and there has been continued effort in the investigation of the thermal characteristics of the gas flame impingement system. Extensive reviews of literatures on impinging flame systems have been given by Viskanta [1], Baukal and Gebhart [2,3] and Chander and Ray [4].

By impinging the flame on the target, forced convection greatly enhances the heat transfer rate. So, significant attention has been paid to the heat transfer characteristics of the impinging flame system. The flame impingement heat transfer characteristics of a single impinging premixed flame have been studied by many researchers [5–7]. The heat transfer behaviors of a slot impinging premixed flame have been investigated by Dong et al. [8]. They also extended their investigations to an array of two and three impinging premixed flames [9,10]. Huang et al. [11] examined the heat transfer characteristics of an impinging premixed flame with induced swirl.

Non-premixed flames have also been used and investigated for impingement heat transfer. Rigey and Webb [12] investigated the flame structure and heat transfer characteristics of an impinging diffusion flame. More recently, the impingement heat transfer from inverse diffusion flames have been examined by several researchers [13–15]. Zhen et al. [16] studied the impingement heat transfer from inverse diffusion flames with induced swirl.

The pollutants emission characteristics of the impinging flame system have been less attacked though they are important. Mishra [17] carried out an investigation of the emissions from a premixed flame impinging onto a flat cold surface. The effects of burner-to-plate spacing, equivalence ratio and Reynolds number on the measured volumetric content of the pollutants in the flue gas were examined. Saha et al. [18] made a study of both the heat transfer and emission characteristics of an impinging rich premixed flame. They also examined the effects of Reynolds number, equivalence ratio and burner-to-plate distance on the volumetric content of CO and NO_x in the flue gas. Mohr et al. [19] made an exhaust gas analysis of an impinging non-premixed flame. The exhaust gases were collected through a quartz probe placed to the outer edge of the impingement plate and in contact with the plate surface. They also obtained volumetric concentrations of CO and NO_x, and compared the pollution formation characteristics of the two flames considered in their study. In the examination of the impinging inverse diffusion flame, Sze et al. [13] sampled the combustion products through a small hole drilled on the impingement plate. They used the measured radial distributions of O_2, CO, CO_2 and NO con-

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Nomenclature

Re	air jet Reynolds number	*H*	nozzle-to-plate distance, m
Φ	overall equivalence ratio	*r*	raidal distance from flame centerline, m

centrations to infer the combustion conditions inside the flame for the purpose of better understanding the heat transfer behaviors.

The pollutants emission from an impinging flame system is a very important behavior of the flame and the emission characteristics of an impinging flame may totally differ from the emission characteristics of the same flame in the open environment. However, there are only a few studies conducted in this field and the previous studies only examined the local volumetric concentrations of the pollutants inside the flame or the exhaust gas without measuring the overall pollutants emission from the impinging flame system. Therefore, the objective of this study is to quantitatively evaluate the overall pollutants emission from an impinging inverse diffusion flame (IDF) system in terms of emission index. The effects of air jet Reynolds number, overall equivalence ratio and nozzle-to-plate distance on the emission index of the pollutants of CO and NO_x will be studied in details. The flames under consideration include swirling and non-swirling IDFs, and hence comparisons of the emission index are made both between the impinging swirling IDF and open swirling IDF, and between the impinging swirling IDF and impinging non-swirling IDF.

2. Experimental setup and method

The experimental apparatus is schematically shown in Fig. 1. The flame from the burner impinges vertically normal to a flat surface. The flat surface is a circular copper plate with a radius of 200 mm and 10 mm thick. The copper plate is evenly cooled on the backside by a cooling water jacket and the temperature of cooling water is maintained at 38 °C by a thermostat to avoid condensation. In the center of the copper plate, there is a small hole of 1 mm diameter, which was used as a probe for sampling in-flame local gases from the flame layer adjacent to the flat surface. For quantifying the overall pollutants emission, the hood method proposed by Butcher et al. [20] and validated by Tremeer and Jawurek [21] was used. A conical stainless steel hood of 600 mm base-diameter and 600 mm in height was placed over the impingement plate to collect the exhaust products. After the flame impinges onto the copper plate, it develops radially outwards along the surface of the plate. When the radially outgoing exhaust gases go beyond the edge of the copper plate, they turn upwards due to buoyancy into the conical hood. The cover at the outlet of the hood is adjustable so as to control the flow rate inside the hood. The flow rate is controlled such that no flue gases run away from the base of the hood to guarantee that the hood collects all the gases from the combusting flame. When the flow inside the hood achieves equilibrium, the flue gases collected in the hood become well-mixed mixtures at the upper portion of the hood. And at several different openings at the outlet of the hood, as shown in Fig. 1, both the gas temperature and pollutants concentration are uniform.

The emission measurements were performed in two series. One is for in-flame local pollutants concentration measurement, and the other is for the overall pollutants emission measurement. In the former case, the gases sampled by the 1-mm hole on the copper plate go through an 1-m long stainless steel tube for cooling down below 60 °C and then enter the NO/NO_x analyzer (California Instruments Corporation, Model 400) and the CO/CO_2 analyzer (California Instruments Corporation, Model 300) to obtain the volumetric concentration of gaseous species including CO and NO_x. In the latter case, the 1-m long stainless steel tube was connected to one of those openings at the outlet of the hood. Water vapor is condensed and removed from the samples before they enter the same NO/NO_x analyzer (CLA) and CO/CO_2 (NDIR) analyzer. Zero and span calibrations were performed before and after each measurement.

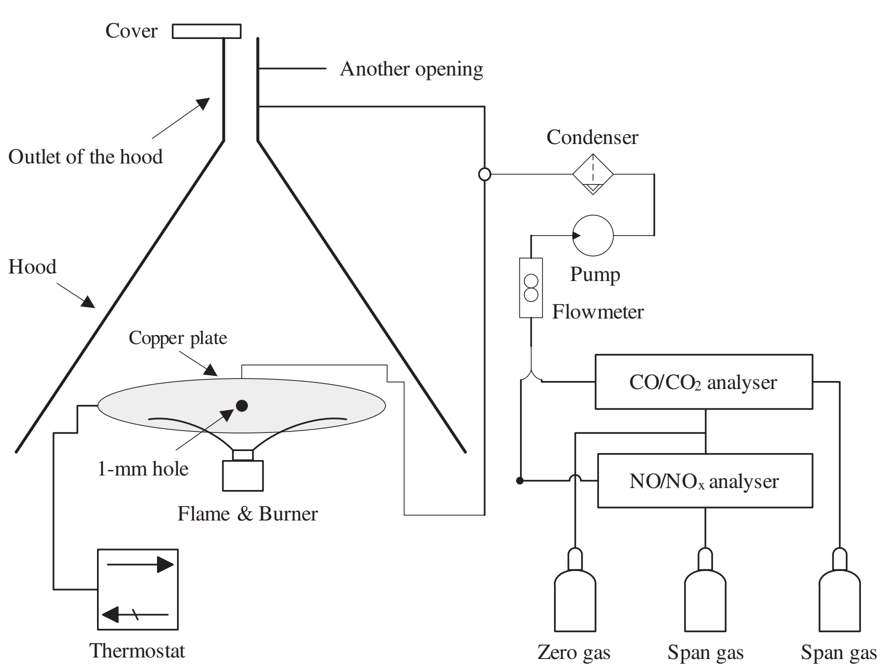

Fig. 1. Experimental apparatus.