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Dynamic sensing of blowout in turbulent CNG inverse jet flame

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The present work focuses on the dynamic blowout sensing of compressed natural gas (CNG) turbulent inverse jet flame (IJF) based on the temporal CH^* chemiluminescence signal acquired from the flame zone. The time varying CH^* chemiluminescence signal exhibits lower fluctuation level for stable IJF. However, higher level of fluctuation in the temporal CH^* intensity is observed as the IJF approaches blowout. In addition, the characterization of CH^* chemiluminescence signature from IJF based on histogram and power spectral density are performed for delineating the stable and unstable IJF. Furthermore, a statistical parameter called normalized root mean square (NRMS), computed from the statistical analysis of CH^* intensity signal is found to be effective in predicting the onset of blowout in CNG IJF. Apart from this, a methodology for sensing the proximity of blowout in CNG IJF is proposed based on NRMS which can be helpful in averting the unexpected blowout in IJF based combustion systems.

1. Introduction

The central oxidizer jet surrounded by annular fuel jet in a coaxial burner establishes a distinct type of jet flame termed as inverse jet flame (IJF). The high momentum central air jet augments the entrainment of low momentum fuel along with the ambient air in the case of open IJF. Apart from this, faster fuel–air mixing can be achieved in this jet flame configuration due to the formation of shear layer eddies at the interface of air–fuel jets. Besides this, the flame structure of inverse jet flame is distinct from the premixed flame and coaxial jet flame established with central fuel jet and annular air jet. Even though IJF is a type of nonpremixed flame, the temperature distribution of IJF and color schlieren visualization reported by Sobiesiak and Wenzell [2] indicated that the portion of IJF is partially premixed. From earlier studies, it can be concluded that a compact blue turbulent jet flame with better thermal and emission characteristics can be obtained by controlling the air–fuel momentum ratio and burner geometry [1–4]. The base flame (see Fig. 1) is a distinct aspect of IJF which is not observed in other jet flame configuration. It helps in anchoring the entire flame to the burner rim and prevents flame lift-off toward blowout. The base flame also helps in sustaining the main flame (see Fig. 1) at higher central air jet velocity by acting as a pilot flame [5]. In addition, the blowout characteristics of IJF are found to be quite different from that of premixed flames due to the presence of base flame in IJF [5]. The post flame NO_x emissions can be reduced drastically in IJF configuration by increasing the central air jet momentum [6]. The turbulent inverse jet flame finds application in various fields namely rocket engines, staged combustion systems, impingement heating, etc. The injection of central oxidizer with annular hydrogen jet in rocket engine combustors helps in minimizing the oxidation of combustor walls [7]. It has been reported that methane–oxygen IJF helps in producing enhanced radiation heat flux as compared to the normal jet flame established with central fuel and annular oxygen jets [8]. In addition to this, the heat transfer rate of IJF is found to be superior as compared to that of premixed flames and hence, this flame configuration can be a potential candidate for impingement heat transfer applications [9].

The chemiluminescence signal from certain excited radicals such as OH^*, CH^* and C_2^* formed in the flame surface has been used as a viable method for real time monitoring of local equivalence ratio in premixed flames and sensing the onset of blowout in lean premixed and partially combustion systems because of its non-intrusive nature and faster response [10–13]. Hardalupas and Orain [10] utilized the chemiluminescence signature of OH^*, CH^* and C_2^* radicals from premixed methane counterflow flames for obtaining a relationship between chemiluminescence intensity and mixture equivalence ratio. Their results revealed the monotonic dependence of OH^*/CH^* ratio on the mixture equivalence ratio of premixed counterflow flame. In addition, they argued that the chemiluminescence from OH^* and CH^* radicals can be used as effective markers for the heat release rate in premixed counterflow flames. Later, Cheng et al. [11] utilized the chemiluminescence of OH^*, CH^* and C_2^* radicals for observing the spatial variation of local

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Nomenclature

IJF	inverse jet flame
MR	air–fuel momentum ratio
NCI	normalized CH* intensity
NRMS	normalized root mean square
PSD	power spectral density
PDF	probability density function
V_a	air jet velocity
V_f	fuel jet velocity

equivalence ratio in swirling partially premixed methane flame. Muruganandam [12] proposed the methodology of utilizing the chemiluminescence signature of OH* radical for sensing the onset of lean blowout (LBO) in swirling methane lean premixed combustor. He introduced the statistical measures such as standard deviation, skewness and kurtosis of the temporal OH* chemiluminescence signal from the flame zone for sensing the proximity of lean blowout in lean premixed combustor. Recently, Yi and Gutmark [13] used OH* chemiluminescence signature for real time prediction of lean blowout in partially premixed 1-decene fueled combustor. They introduced two statistical quantities such as normalized root mean square (NRMS) and cumulative duration of LBO precursor events for lean blowout prediction in gas turbine combustors. Later, Bompelly et al. [14] proposed a new measure called statistical index from the analysis of OH* chemiluminescence signature for predicting the proximity of blowout in lean premixed combustor. Mukhopadhyay and Ray [15] developed the symbolic time series analysis of CH* chemiluminescence signature for predicting the lean blowout in lean premixed combustor. Recently, Gotoda et al. [16,17] characterized the dynamic behavior of combustion instability in lean premixed combustor by analyzing its pressure fluctuation signal using nonlinear time series analysis and dynamical systems theory respectively.

From the literature, it can be concluded that chemiluminescence signature from predominant radicals can be useful in the real time monitoring of local equivalence ratio and heat release rate in open flames. Apart from this, chemiluminescence signature is also utilized for sensing the onset of blowout in lean premixed and partially premixed flame based combustors. However, the prediction of lean blowout in the case of open flames using chemiluminescence signature has not been investigated extensively to the best of our knowledge. There is a renewed interest in the development of rocket engines which utilizes full flow staged combustion cycle (FFSC). In the case of FFSC rocket engine, gaseous oxygen is injected through shear coaxial injector with annular gaseous hydrogen [18]. The gas–gas shear coaxial injector configuration helps in stabilizing jet flame similar to that of IJF with shorter flame height [7]. Because of the varied applications of IJF ranging from rocket engines to impingement heating burner systems, there is a need for sensing the onset of blowout in turbulent IJF which is crucial for averting unexpected blowout in rocket combustors and gas burners. The chemiluminescence signature from IJF can be utilized for its blowout prediction because of its non-intrusive nature and faster response. However, no work on the prediction of the onset of blowout in IJF using its chemiluminescence signature exists in open literature to the best of our knowledge. This forms the major motivation for the present work. An attempt has been made in this paper to sense the onset of blowout in IJF using the chemiluminescence signature of CH* radical, which is one of the predominant radical with a distinct wavelength generated in the flame. Apart

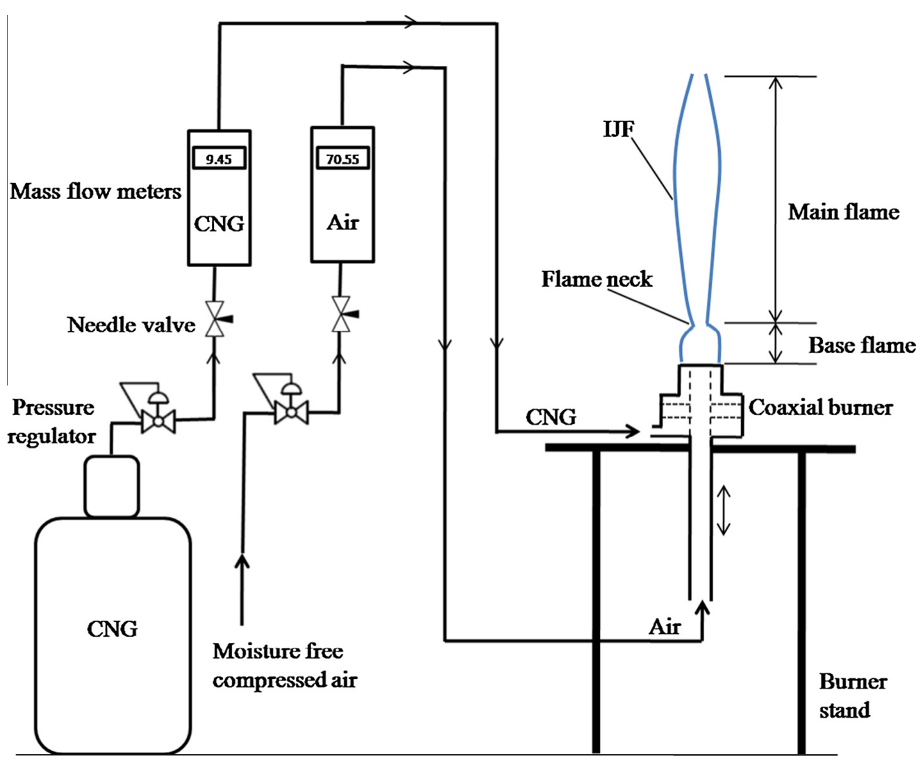

Fig. 1. Schematic of the experimental setup [5].