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1 **Paper- IM-15-10099R**

2

3 Title: Quantitative assessment of flame stability through image processing and spectral
4 analysis

5

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Abstract

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This paper investigates experimentally two generalized methods, i.e., a simple universal index and oscillation frequency, for the quantitative assessment of flame stability at fossil-fuel-fired furnaces. The index is proposed to assess the stability of flame in terms of its color, geometry, and luminance. It is designed by combining up to seven characteristic parameters extracted from flame images. The oscillation frequency is derived from the spectral analysis of flame radiation signals. The measurements involved in these two methods do not require prior-knowledge about fuel property, burner type and other operation conditions. They can therefore be easily applied for flame stability assessment without costly and complex adaption. Experiments were carried out on a 9MWth heavy-oil-fired combustion test rig over a wide range of combustion conditions including variations in swirl vane position of tertiary air, swirl vane position of secondary air, and ratio of primary air to total air. The impact of these burner parameters on the stability of heavy oil flames is investigated by using the index and oscillation frequency proposed. The experimental results obtained demonstrate the effectiveness of the methods and the importance of maintaining a stable flame for reduced NO_x emissions. It is envisaged that such methods can be easily transferred to existing flame CCTV (Closed-Circuit Television) systems and flame failure detectors in power stations for flame stability monitoring.

Keywords: flame stability, flame monitoring, digital imaging, image processing, spectral analysis, oscillation frequency, NO_x emission

Highlights

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- A simple universal index is proposed for the quantitative assessment of flame stability in industrial boiler. The index assesses the stability of flame in terms of its color, geometry, and luminance.
- Experiments were carried out on a 9MW_{th} industrial scale heavy-oil-fired combustion test rig over a wide range of combustion conditions to demonstrate the effectiveness of the proposed index and oscillation frequency for flame stability monitoring.
- Experimental results show that the lowest NO_x emission is generally observed under the most stable flame condition, which indicates the importance of maintaining a stable flame for reduced NO_x emissions and the necessity of the flame stability assessment.
- The presented methods can be transferred easily to existing flame CCTV systems and flame failure detectors in power stations.

82 **1. Introduction**

83

84 Fossil-fuel-fired furnaces are widely used in power generation industry for electricity
85 generation. A common problem that occurs in the furnace is the instability of the flame. The
86 problem has become severe due to the recent trend of using low quality fuel, fuel blends and
87 co-firing of biomass with fossil fuels. A unstable flame causes many combustion problems
88 such as, low combustion efficiency, high NO_x emissions and furnace safety (e.g., increased
89 wall thermal stress, and vibration of the furnace) [1]. Therefore, a reliable and effective means
90 for the on-line continuous monitoring and quantification of flame stability is becoming
91 increasingly crucial for maintaining the optimized performance of the furnace.

92

93 The stability of flame is a broad concept largely relating to the ignition stability of fuel, air-to-
94 fuel ratio, the balance between the velocities of the flame and air-fuel mixture, and the
95 thermal-acoustic stability between the heat release and acoustic oscillations [2, 3]. The
96 ultimate aim of retaining the flame stability in a combustion system is to achieve optimized
97 combustion process, i.e., high combustion efficiency, low pollutant emissions (e.g., NO_x) and
98 safe plant operation. Significant research has been conducted to investigate the mechanism
99 and characteristics of flame instability [4-6] theoretically and experimentally by using various
100 monitoring diagnostic methods such as Laser Induced Fluorescence [7], infrared absorption
101 [8] and CCD (Charge-Coupled Device) cameras [9, 10]. A great deal of efforts have also been
102 devoted to the study of flame stability limit [11] and diagram [12-14], which generally
103 correspond to a specific fuel and burner, and gives the range of controllable parameters (e.g.,
104 equivalence ratio, fuel stream velocity and heat input rate) within which blow-off and
105 flashback can be avoided for a safety purpose. However, very limited work focused on the
106 quantitative assessment of the flame stability for industrial combustion applications, which is

107 an essential step to advanced flame monitoring and diagnostics, and thus combustion
108 optimization. The technical challenges are thought to lie in two aspects. Firstly, there is
109 currently no well-defined criterion about the flame stability as well as on-line assessment
110 method in the combustion domain, even though an unstable flame has been identified as one
111 of main causes of many combustion problems for decades. This is mainly ascribed to the fact
112 that a flame is a three-dimensional thermo-fluid-dynamic field associated with many
113 combustion phenomena including heat, light, sound, pressure, and so on. This nature of flame
114 has led to the investigation of the flame stability through different perspectives. It also gives
115 rise to the difficulty, if not impossibility, in comprehensively defining flame stability by a
116 single or a few parameters. Regardless of the nature of the flame sensorial data that are
117 available to a flame monitoring system (e.g., planar laser induced fluorescence images,
118 chemiluminescence images, pyrometry-derived temperature maps, or non-filtered images), it
119 is very challenging to establish a methodology to process those data to quantify the stability
120 of the flame. Secondly, difficulties are associated with practical issues including the
121 accessibility of the furnace for a flame monitoring system and the protection of such a system
122 from the high temperature and fouling in the furnace [15]. These practical issues give rise to
123 considerable constrains in applying some of flame diagnostic techniques, such as laser-based
124 systems, to long-term routine operation in a power station environment [16].

125

126 The techniques that are currently available for flame monitoring at power stations are limited,
127 mainly flame failure detectors and CCTV systems, due to a number of factors such as
128 restricted access, harsh environment, high cost, and safety reasons. Flame failure detectors are
129 based on ultraviolet, visible or infrared sensing, and capture flame radiation signals. However,
130 these detectors can indicate only flame presence or absence for safety purposes, though they
131 are equipped in most of furnaces as a compulsory device. Flame visualization techniques have

132 increasingly been used as a diagnostic tool in the understanding and optimization of
133 combustion processes, as they provide spatial and temporal information about the thermal and
134 chemical characteristics of flames [15, 17]. Passive imaging techniques, unlike laser-based
135 active imaging techniques, avoid the need for external illumination or seeding. They record
136 directly the radiation emitted by the flame and have been identified as the one of the most
137 effective flame visualization methods for industrial applications. The CCTVs, as the simplest
138 passive imaging system, have already been installed in boilers at many power stations as an
139 auxiliary flame monitoring technique of flame failure detection. However, CCTVs are only
140 for general surveillance purposes and the interpretation of flame images is based on
141 operator's experience.

142

143 A multi-functional instrumentation system for flame monitoring in industrial furnaces was
144 developed [18, 19]. The system incorporates digital imaging and photo-detector techniques
145 and is capable of capturing flame images and radiation signals simultaneously and producing
146 a range of characteristic parameters of the flame on an on-line basis. Efforts have also been
147 made to assess the flame stability through the statistical analysis of physically meaningful
148 parameters extracted from flame images (e.g., ignition point, luminous region, brightness,
149 non-uniformity and temperature) and through spectral analysis of flame radiation signals [19].
150 Although many features (parameters) can be extracted from flame images and spectral
151 signals, however, they vary significantly from case to case and some features may be
152 significant only under specific cases. For instance, flame ignition points can be observed only
153 if the flame is detached from the nozzle of the burner. For an un-detached flame, the flame
154 ignition points are not applicable. Therefore, it is critical, from a practical operation point of
155 view, to devise more generalized criterion that can be used for assessing for the flame
156 stability, particularly where combustion systems use different types of fuels (e.g., gas, oil,

157 coal, and biomass), and operate under different conditions (e.g., over-fire air, flue gas
158 recirculation and etc.).

159

160 The work presented in this paper focuses on establishing a generalized method for the
161 quantitative assessment of the flame stability. A universal flame stability index is defined and
162 used to assess the stability of flame in terms of its color, geometry, and luminance. The index
163 is derived from the statistical analysis of up to seven individual characteristic parameters
164 extracted from flame images. In [20], the concept of the flame stability index and the
165 preliminary results of using such as concept for the flame stability assessment were firstly
166 reported. In the paper, the thorough theory of the flame stability index and the detailed
167 procedure of using the stability index for the flame assessment are introduced. Experiments
168 are conducted on a 9MW_{th} industrial-scale heavy-oil-fired combustion test facility over a
169 wide range of combustion conditions. The impacts of various burner parameters on flame
170 stability are studied by the proposed index. The correlation between the flame stability and
171 NO_x emissions is also investigated. In addition, the oscillation frequency, which was defined
172 as a characteristic frequency of flame radiation signal [21], was suggested to be relevant with
173 flame stability to a degree, but very limited experimental studies have been reported. In this
174 study the oscillation frequency incooperates with the proposed stability index, forming the
175 generalization of these two measurement approaches for the flame stability assessment.

176

177 The main contributions of this study lie in the proposed definition of the universal flame
178 stability index, and the demonstration of this index together with the flame oscillation
179 frequency for assessing quantitatively the flame stability under a wide range of heavy-oil-
180 fired combustion conditions. The proposed method does not require prior-knowledge about
181 fuel property, burner type and other operation conditions, and therefore can be easily applied

182 for flame stability assessment without ad hoc and costly adaption for new applications. It
183 should be stressed that the validation of the proposed approach for the quantitative assessment
184 of the flame stability is conducted experimentally, and the mathematical modelling of flame
185 stability is beyond the scope of this paper. It is realized that the mathematical modelling
186 techniques such as CFD (Computational Fluid Dynamics) modelling provide very powerful
187 tools in designing and analyzing combustion systems. However, due to a number of factors, it
188 is still very difficult to use these modelling techniques to provide with the quantitative and
189 reliable predication of combustion parameters, and subsequently flame stability, especially for
190 large industrial boilers. These factors include the lack of reliable flame models, the need for
191 high performance computational systems, the intrinsic uncertainty and variations in
192 combustion systems and fuels burnt, the absence of a well-defined criterion about flame
193 stability, and so on. These factors are also the main reason that the permanent supervision of
194 flame is needed in industrial boilers.

195

196 The paper is organized as follows: Section 2 presents the detailed description of the proposed
197 methodology for the quantitative flame stability assessment is given in. Section 3 gives the
198 experimental results and discussion of applying the proposed technical approach for assessing
199 the flame stability on a 9MWth heavy-oil-fired combustion test rig. Section 4 remarks the
200 findings derived from this study and future research directions.

201

202 **2. Methodology**

203

204 The present work assesses the stability of a flame through the analysis of flame images and
205 radiation signals, as flame instability generally occurs with large fluctuations in flame
206 geometry, radiation intensity, or temperature (contained in color information). The proposed

207 index and oscillation frequency quantify these fluctuations hence the flame stability to some
208 degree in a relative way.

209

210 2.1 System set-up

211

212 Figure1 shows the block diagram of the flame stability assessment system. The system
213 mainly consists of a 90° viewing-angle optical probe protected by a water-cooling jacket, a
214 beam splitter, a 1/3 inch CMOS RGB digital camera (UI-1640SE) with 1.3-million pixels
215 (1280H×1024V), an embedded photo-detector and signal-processing board, and a high-
216 performance embedded-motherboard with dedicated application software. All these optical
217 and electronic components are integrated into a single compact unit offering the system high
218 portability and robustness. The optical probe is used to transmit the light of the flame inside
219 the combustion chamber to the camera and photo-detector (CENTRONIC, OSD1-5T)
220 simultaneously with the aid of the beam splitter. The flame images and radiation signals are
221 processed to derive the proposed stability index and oscillation frequency on an online basis,
222 by the embedded-motherboard and the signal-processing board, respectively. The results are
223 transmitted to remote control room via Ethernet. The detailed description about the design,
224 implementation and evaluation of the system can be found in [19].

225

226 2.2 Measurement principles

227

228 2.2.1 Definition of the flame stability index

229

230 As flame images provide valuable information on the spatial and temporal dynamics of the
231 flame, it is naturally considered to assess the stability of flame through its images. However,

232 apart from the characteristics of imaging system used to capture flame images, the quality and
233 content of the obtained images are closely relevant with many application-related factors such
234 as fuel properties, burner type, combustion condition, and system installation. These factors
235 may vary dramatically in different cases. Therefore, it is desirable to have a generalized
236 criterion that can be used for assessing for the flame stability under different combustion
237 conditions. The concept of flame stability index is then proposed for this purpose. In this
238 study, the flame stability index combines the dynamic characteristics of seven parameters
239 derived from flame images. The seven parameters are concerned with color, geometry, and
240 luminance. Figure 2 shows the measurement procedure of the index, which can be divided
241 into three steps, i.e., transformation of color space, extraction of parameters, and data fusion.

242

243 2.2.1.1 Color space transformation from RGB to HSI

244

245 The first step is to transform the format of a color image from original RGB (Red, Green and
246 Blue) to HSI (Hue, Saturation and Intensity). The color characteristic of a flame is closely
247 linked with the flame emission spectra and largely dependent on the fuel properties, air
248 supply, and temperature. The flame color characteristic should therefore be taken into a
249 consideration when evaluating the flame stability. The RGB color space is useful for color
250 display, where the color and intensity are inseparably stored in the three primary color
251 components. However, the R, G, and B components in the RGB space are highly correlated
252 [22]. When the intensity changes, all the three components will change accordingly. It is
253 therefore not good for color analysis. The HSI model is another commonly used color space
254 in image processing, in which the color information of an image is separated from its intensity
255 information. The Hue (H) component represents the dominant wavelength in the spectral
256 distribution of light wavelengths, indicating basic colors. The Saturation (S) component is a

257 measure of the purity of the color, denoting the amount of white light mixed with the hue.
 258 The Intensity (I) component is determined by the amount of light, describing the brightness of
 259 the image [22].

260

261 The HSI color model can be described geometrically as in Figure 3. The H component
 262 describes the color in the form of an angle between a reference line and the color point. The
 263 range of the H value is generally from 0° to 360°; for example, red is 0°, yellow is 60°, green
 264 is 120°, and magenta is 300°. For the convenience of analysis, the H value is normalized by
 265 360° in the present study. The S component represents the perpendicular distance from the
 266 color point to the axis. The range of S component is [0, 1]. The nearer the point is to the
 267 center axis, the lighter is the color. The I component is the height of the color point in the axis
 268 direction, ranging from 0 to 1 where 0 represents black and 1 means white. Each slice
 269 perpendicular to the axis is a plane with the same intensity.

270

271 The HSI coordinates can be transformed from the RGB space as follows:

$$272 \quad H = \begin{cases} \cos^{-1} \left\{ \frac{\frac{1}{2}[(R-G)+(R-B)]}{[(R-G)^2+(R-B)(G-B)]^{1/2}} \right\} / 360^\circ, & \text{if } B \leq G \\ 1 - \cos^{-1} \left\{ \frac{\frac{1}{2}[(R-G)+(R-B)]}{[(R-G)^2+(R-B)(G-B)]^{1/2}} \right\} / 360^\circ, & \text{if } B > G \end{cases} \quad (1)$$

$$273 \quad S = 1 - \frac{3}{R+G+B} \cdot [\min(R, G, B)], \quad (2)$$

$$274 \quad I = \frac{R+G+B}{3}. \quad (3)$$

275

276 2.2.1.2 Extraction of parameters

277

278 The second step is to derive flame parameters from HSI images. Seven parameters, assigned
 279 as M_H , M_S , M_I , C_H , C_S , C_I , and A_I , are extracted. M_H , M_S , and M_I denote the mean values of

280 H, S and I components, respectively, whilst C_H , C_S , and C_I are the contrast values of the
 281 three components. A_I represents the flame area, which is derived from I image.

282

283 The mean M_k and contrast C_k (pixel) of an image are defined as (4) and (5), respectively,

$$284 \quad M_k = \frac{1}{P \times Q} \sum_{i=0}^{P-1} \sum_{j=0}^{Q-1} V_k(i, j), \quad (4)$$

$$285 \quad C_k = \left(\frac{1}{P \times Q} \sum_{i=0}^{P-1} \sum_{j=0}^{Q-1} (V_k(i, j) - M_k)^2 \right)^{1/2}, \quad (5)$$

286 where $k=H, S, I$, and $V_k(i, j)$ is the i -th j -th element of the two dimensional image with a size
 287 $P \times Q$ pixels.

288

289 The flame area, A_I (pixel²), is determined by applying an appropriate threshold (estimated
 290 from the maximum background noise) to the I image, i.e.,

$$291 \quad A_I = \frac{1}{P \times Q} \sum_{i=0}^{P-1} \sum_{j=0}^{Q-1} \begin{cases} 1, & \text{if } V_I(i, j) > \text{threshold} \\ 0, & \text{other} \end{cases}. \quad (6)$$

292

293 2.2.1.3 Data fusion

294

295 The last step is to fuse the standard deviations of the extracted parameters to derive the
 296 universal stability index (δ) in the form as,

$$297 \quad \delta = \prod_{i=1}^7 \left(\frac{\phi(P_i) - \sigma_{P_i}}{\phi(P_i)} \right)^{w_i} \in [0, 1], \quad (7)$$

298 where $P_i \in \{M_H, M_S, M_I, C_H, C_S, C_I, A_I\}$, and σ_{P_i} is the standard deviation of P_i . $\phi(P_i)$ is
 299 the theoretical maximum standard deviation of P_i and is used to limit the index boundary to
 300 $[0, 1]$. w_i is the weight for P_i . In the present work, the same weight $w_i=2$ was assigned for all

301 the parameters, which means that all flame parameters are taken as equally important. In a
 302 specific case, a larger weight can be given to the parameter that is more important than others.

303

304 It should be note that although quantities P_i possess different physical meanings, they are
 305 normalized by their theoretical maximums, and so the normalized quantities are
 306 dimensionless and have the same range [0, 1]. After normalization, these quantities are
 307 combined in such a form of (7) that, if there is any large variation in any of these quantities,
 308 which indicates the unstable flame, it will be indicated by this combined index.

309

310 The theoretical maximum standard deviation of a variable x , $\phi(x)$, depends on the dynamic
 311 range and probability distribution of x . Suppose $x = \{x_i | i = 1, 2, \dots, N, x_i \in [L_1, L_2]\}$ with a
 312 unknown probability distribution, the mean and standard deviations of x are denoted as μ_x
 313 and σ_x , respectively,

$$314 \quad \mu_x = \frac{1}{N} \sum_{i=1}^N x_i, \quad (8)$$

$$315 \quad \sigma_x = \left(\frac{1}{N} \sum_{i=1}^N (x_i - \mu_x)^2 \right)^{1/2}. \quad (9)$$

316 Rearranging (9) yields

$$317 \quad \sigma_x = \left(\frac{1}{N} \sum_{i=1}^N \left(x_i - \frac{L_2 - L_1}{2} \right)^2 - \left(\mu_x - \frac{L_2 - L_1}{2} \right)^2 \right)^{1/2}. \quad (10)$$

318 Considering $\frac{1}{N} \sum_{i=1}^N \left(x_i - \frac{L_2 - L_1}{2} \right)^2 \geq \left(\mu_x - \frac{L_2 - L_1}{2} \right)^2 \geq 0$ yields

$$319 \quad \sigma_x \leq \left(\frac{1}{N} \sum_{i=1}^N \left| x_i - \frac{L_2 - L_1}{2} \right|_{\max}^2 \right)^{1/2} \leq \frac{L_2 - L_1}{2}. \quad (11)$$

320 The maximum value of $\frac{L_2-L_1}{2}$ is achieved if and only if $\mu_x = \frac{L_2-L_1}{2}$ and $x_i = 0$ or $\frac{L_2-L_1}{2}$ for $i=1,$
321 $2, \dots, N$. In other words, the theoretical maximum standard deviation of x , $\phi(x)$, equals to a
322 half of the dynamic range, i.e.,

$$323 \quad \phi(x) = \frac{L_2 - L_1}{2}. \quad (12)$$

324

325 The dynamic ranges of H, S, and I are [0, 1], determining that $\phi(M_H)$, $\phi(M_S)$, $\phi(M_I)$ and
326 $\phi(A_I)$ are 0.5, while $\phi(C_H)$, $\phi(C_S)$ and $\phi(C_I)$ are 0.25.

327

328 The features of the proposed index are summarized as follows. Firstly, the index evaluates
329 the stability of a flame through analyzing dynamics of its color, luminance and geometry.
330 Secondly, the index has a fixed boundary, ranging from 0 to 1, which is desirable in
331 metrology. The highest value '1' is achieved if and only if all parameters are constant with
332 time, indicating a perfectly stable state. The lowest value '0' occurs when the standard
333 deviation of any parameter reaches its theoretical maximum value, indicating an extremely
334 unstable state. Last but not least, the index is computationally simple, suitable for on-line
335 measurement. The measurement procedure does not depend on fuel properties, furnace types,
336 or combustion conditions, and thus can be applied to new applications without any ad-hoc
337 and costly adaption.

338

339 2.2.2 Spectral analysis and oscillation frequency

340

341 As can be observed by human eye, most flames exhibit certain spatial and temporal dynamic
342 patterns. The dynamic patterns can be revealed to a degree in the power spectrum of flame
343 radiation signals to give an indication about the stability of a flame. Previous studies have

344 suggested that the low frequency components of flame signals could be ascribed to flame
345 geometrical fluctuations due to aerodynamic or convective effect, whilst high frequency
346 components could be due to the energy transitions among intermediate radicals or variations
347 in the energy emission rate of reacting species [23]. In the present work, it was hoped that the
348 spectral analysis of flame signals can be used to provide an insight into the validity of the
349 proposed stability index.

350

351 The power spectral density (PSD) of a flame radiation signal can be derived from

352
$$P(f) = \frac{1}{N_1} \left(X_{N_1}(f) \right)^2, \quad (13)$$

353 where $P(f)$ is the PSD estimate, and $X_{N_1}(f)$ is the Fourier Transform of N_1 -point sampling
354 data sequence $X_{N_1}(f)$ of the signal. The data length N_1 , for Fast Fourier Transform, is 1024
355 in this study.

356

357 The oscillation frequency of flame was proposed previously [21] as a characteristic frequency
358 of the PSD and suggested to be relevant with flame stability. It is defined as the power-
359 density weighted average frequency over the entire frequency range, i.e.,

360
$$F = \frac{\sum_{i=1}^{N_2} p_i \cdot f_i}{\sum_{i=1}^{N_2} p_i}, \quad (14)$$

361 where F is the oscillation frequency, f_i is the i th frequency, p_i is the power density of the i th
362 frequency component, and N_2 is the number of frequency components. The effectiveness of
363 using the oscillation frequency as a quantitative flame stability indicator is investigated
364 experimentally in the following section.

365

366 3. Experimental Results and Discussions

367

368 Experimental work was undertaken on a 9MW_{th} industrial-scale heavy-oil-fired combustion
369 test facility, as illustrated in Figure 4. The furnace is equipped a single low NO_x burner in a
370 horizontal cylindrical combustion chamber with 11 meters in length and 1.3 meters in
371 diameter [19]. Heavy oil was atomized by steam and injected into the combustion chamber
372 through an oil gun, and then mixed with surrounding primary air (PA), secondary air (SA),
373 and tertiary air (TA) successively. The flame imaging system penetrated the furnace through
374 a side port close to the front wall (Figure 4) to visualize the root part of the flame as the
375 central reaction zone. A wide range of combustion conditions were created, including
376 variations in the swirl vane position of the tertiary air, the swirl vane position of the
377 secondary air, and the ratio of the primary air to total air. The impacts of these burner
378 parameters on the stability of heavy oil flames are investigated. During all these tests, the
379 total air flow rate (9100Nm³/h) and the oil flow rate (800kg/h) were kept constant. The NO_x
380 emissions of flue gas were measured concurrently by a gas analyzer during the tests.

381

382 3.1 Effects of the swirl vanes on flame stability

383

384 The swirling of air flow affects considerably the intermixing of the atomized oil fuel and air
385 flow hence the flame stability and combustion performance. The adjustable settings of the
386 combustion test facility that are capable of controlling the swirling of air flow include the
387 swirl vane angle of the TA and the swirl vane position of the SA.

388

389 The TA swirl vane angle determines the direction of the tertiary air flow. It is defined as the
390 angle between the swirl vane and the plane perpendicular to the burner axis, varying from 0°

391 (air inlet fully closed) to 90° (air inlet fully open but without any swirl). Under the same air
392 flow rate, a smaller swirl angle gives a stronger swirling intensity. Three different angles,
393 25°, 35°, and 45°, were created during the test. Figure 5 shows the typical example of
394 instantaneous flame images for different TA swirl vane angles.

395

396 The effects of the TA swirl vane angle on the flame stability were previously investigated in
397 [19] in terms of geometrical, luminous and fluid-dynamic characteristics. Some of the results
398 are briefly re-presented here for comparison with the results from the proposed index and for
399 completeness of the study. It was previously found that a TA swirl vane angle 25° resulted in
400 significantly increased amplitude of low frequency components (Figure 6b) and decreased
401 oscillation frequency (Figure 6c) [19], indicating great geometrical fluctuation and decreased
402 flame stability. The result from measured flame stability index is consistent with this finding,
403 as shown in Figure 6a. The stability index increased gradually with the vane angle, which
404 confirms that an increased TA swirl vane angle would result in improved flame stability. The
405 lowest stability index is observed at 25°, indicating the flame is relatively unstable under
406 such a swirl vane angle setting.

407 The SA swirl vane position controls the amount of air going through the SA swirl vane. For
408 the SA, part of the air flow goes through the swirl vane, and the rest bypasses the swirl vane
409 and goes straightforward into the combustion chamber. The lower the swirl vane position,
410 the more air goes through the swirl vane, and the stronger the swirling intensity. During the
411 test, three different SA swirl vane positions, i.e., -17mm, 30mm and 65mm, were created.
412 Figure 7 shows the typical example of instantaneous flame images for the different SA swirl
413 vane positions. A direct comparison among the images has suggested that a greater SA swirl
414 vane position resulted in a slightly stretched flame, similar to the effect of a greater TA swirl
415 vane angle. This can be understood by the fact that the stronger the swirling intensity of the

416 secondary air, the more air goes swirly towards away from the burner axis due to the effect
417 of centrifugal force, resulting in a wide spread angle of the flame.

418

419 Figure 8a shows the stability indices at SA swirl vane positions -17mm and 30mm are
420 relatively low, indicating an unstable flame under these two conditions. The highest stability
421 index is observed at 65mm, indicating an improved flame stability. This result is supported by
422 the power spectral analysis and NO_x emissions. The increase of the SA swirl vane position
423 gave rise to increased amplitudes in both the low- and high-frequency components (Figure
424 8b), suggesting that the SA swirl vane position has a significant impact on both the
425 geometrical and kinetic characteristics of the flame. Figure 8d shows that the lowest NO_x
426 emission was observed at the stability-improved condition, which is consistent with the result
427 obtained from the TA swirl vane angle test (Figure 6d). It should also be noted that under this
428 test the flame stability index gives a better indication than the oscillation frequency. As can be
429 seen in Figure 8c, the oscillation frequency failed to indicate the variations in the flame
430 stability caused by a change in the SA swirl vane position. This is due to the intrinsic
431 limitation imposed by the definition of the oscillation frequency as the weighted average
432 frequency over the whole spectrum.

433

434 3.2 Effects of the ratio of primary air to total air on flame stability

435

436 The purpose of this test was to investigate the impacts of the spatial distribution of air flow on
437 the flame stability. During the test, the ratio of the SA to total air (SA ratio) (43%) provided
438 for the burner was kept constant. When the PA ratio increased, the TA ratio decreased by the
439 same degree correspondingly. Five different PA ratios, i.e., 11%, 14%, 17%, 20% and 23%

440 were tested. Figure 9 shows the typical instantaneous images of the flame under different PA
441 ratios.

442

443 Figure 10a shows the variations of the measured stability index with the PA ratio. With the
444 increase of the PA ratio, the index increased gradually, indicating an improved stability. The
445 lowest value is obtained at PA 11%, indicating the flame is comparatively less stable under
446 such a PA ratio. This result is in line with the spectral analysis, as illustrated in Figure 10b.
447 The much higher amplitude of the low-frequency components, which results in the lowest
448 oscillation frequency among the five tested conditions (Figure 10c), is observed at PA 11%,
449 indicating an increased geometrical fluctuation and decreased instability at such a condition.
450 The highest NO_x emission also emerged at PA 11% (Figure 10d) and decreased gradually
451 with the PA ratio, implying that the improved flame stability gave rise to lower NO_x
452 emissions.

453

454 3.3 Correlations between flame stability and NO_x

455

456 In the above experiments, for a specific test, the lowest NO_x emission is generally observed
457 under the most stable flame condition. To investigate further this phenomenon, data were
458 collected from a wider range of combustion conditions including variations in overfire air to
459 total air ratio and injection position [24]. Under all the conditions, the oil flow rate and the
460 total air flow rate were kept constant for a fair comparison. Figure 11a gives the comparison
461 between the measured flame stability index and corresponding NO_x emissions during all the
462 tests. It is evident that the volume of NO_x emissions in the flue gas decreases gradually with
463 an improved flame stability. This finding is also supported by the results of the oscillation
464 frequency (as show in Figure 11b), which shows low NO_x emissions were achieved generally

465 with a high oscillation frequency, indicating a better flame stability. The results presented
466 show the importance of maintaining a stable flame and the necessity of the flame stability
467 assessment. It should be mentioned that the results do not imply that flame stability can be
468 used directly as a predictor of NO_x emissions, as the NO_x formation process is also dependent
469 upon many other factors. However, they exemplify the potentials of using the proposed
470 technique for assessing the performance of combustion system.

471

472 The above experiments (Section 3.1-3.3) demonstrated the effectiveness of the two methods
473 in flame stability assessment. Although the results obtained are preliminary, they are very
474 promising. It can be seen that the two methods can give an indication about the variation of
475 flame stability with different conditions. More importantly, the results from these two
476 different methods are well matched and they gave similar conclusions regarding the trend of
477 NO_x emission with flame stability, which are consistent with past experience. The advantage
478 of these two methods together with the imaging system also lies in its practicality and
479 feasibility for use in large scale industrial boilers, which is difficult to achieve when using
480 some other flame diagnostic techniques.

481

482 **4. Conclusions**

483

484 This paper attempts to devise generalized methods for the quantitative assessment of flame
485 stability in industrial furnaces. A simple universal index, which is derived from the statistical
486 analysis of flame images and assesses the stability of flame in terms of its color, geometry
487 and luminance, has been proposed. The advantages of this index include a fixed range [0, 1]
488 desirable in metrology, and simple computation complexity suitable for on-line processing.
489 The experimental results, obtained under a wide range of combustion conditions on a 9MW_{th}

490 heavy-oil-fired combustion test facility, have demonstrated the effectiveness of the index for
491 the quantitative assessment of flame stability. In addition, the feasibility of the oscillation
492 frequency derived from the flame radiation signal as a simple quantitative indicator of flame
493 stability has also been demonstrated. One important advantage of the index proposed and the
494 oscillation frequency is the generalization of their measurement approaches. This is
495 particularly useful because the concept can potentially be transferred to existing flame
496 CCTV systems and flame detectors in power stations without a costly and complex adaption,
497 This is due to the fact that the flame images captured by the CCTV systems and the flame
498 radiation signals captured by the flame detectors should carry most information which the
499 flame imaging system provide and thus can be used to compute the stability index and
500 oscillation frequency for the quantitative assessment of flame stability. Last but not least, for
501 all different sets of tests, the lowest NO_x emission has generally been observed when the
502 flame is most stable, which indicates the importance of maintaining a stable flame for
503 reduced NO_x emissions. Future research will be directed towards the usage of the technique
504 as an indication or prediction for flame stability problems such as increased wall thermal
505 stress, vibration of the furnace, low combustion efficiency, and high NO_x emissions, and the
506 integration of the technique into industrial boiler control system.

507

508 **Acknowledgment**

509

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515

516 **References**

- 517 [1] A. Fichera, C. Losenno, and A. Pagano, "Experimental analysis of thermo-acoustic
518 combustion instability," *Applied Energy*, vol. 70, pp. 179-191, 2001.
- 519 [2] S. Su, J. H. Pohl, D. Holcombe, and J. A. Hart, "Techniques to determine ignition,
520 flame stability and burnout of blended coals in p.f. power station boilers," *Progress
521 in Energy and Combustion Science*, vol. 27, pp. 75-98, 2001.
- 522 [3] S. Candel, "Combustion dynamics and control: Progress and challenges,"
523 *Proceedings of the Combustion Institute*, vol. 29, pp. 1-28, 2002.
- 524 [4] T. Lieuwen, H. Torres, C. Johnson, and B. T. Zinn, "A mechanism of combustion
525 instability in lean premixed gas turbine combustors," *Journal of Engineering for Gas
526 Turbines and Power*, vol. 123, pp. 182-189, 2001.
- 527 [5] S. Seo, "Combustion instability mechanism of a lean premixed gas turbine
528 combustor," *Journal of Mechanical Science and Technology*, vol. 17, pp. 906-913,
529 2003.
- 530 [6] K. K. Venkataraman, L. H. Preston, D. W. Simons, B. J. Lee, J. G. Lee, and D. A.
531 Santavicca, "Mechanism of combustion instability in a lean premixed dump
532 combustor " *Journal of Propulsion and Power*, vol. 15, pp. 909-918, 1999.
- 533 [7] Y. Wu, Y. Lu, I. S. Al-Rahbi, and G. T. Kalghatgi, "Prediction of the liftoff, blowout
534 and blowoff stability limits of pure hydrogen and hydrogen/hydrocarbon mixture jet
535 flames," *International Journal of Hydrogen Energy*, vol. 34, pp. 5940-5945, 2009.
- 536 [8] J. G. Lee and D. A. Santavicca, "Experimental diagnostics for the study of
537 combustion instabilities in lean premixed combustors," *Journal of Propulsion and
538 Power*, vol. 19, pp. 735-750, 2003.

- 539 [9] X. Paubel, A. Cessou, D. Honore, L. Vervisch, and R. Tsiava, "A flame stability
540 diagram for piloted non-premixed oxycombustion of low calorific residual gases,"
541 *Proceedings of the Combustion Institute*, vol. 31, pp. 3385-3392, 2007.
- 542 [10] D. Y. Kiran and D. P. Mishra, "Experimental studies of flame stability and emission
543 characteristics of simple LPG jet diffusion flame," *Fuel*, vol. 86, pp. 1545-1551,
544 2007.
- 545 [11] M. S. Mansour, "Stability characteristics of lifted turbulent partially premixed jet
546 flames," *Combustion and Flame*, vol. 133, pp. 263-274, 2003.
- 547 [12] C. Lee, C. Hwang, and S. Hong, "Proposal and validation of a new type of flame
548 stability diagram for partially premixed flames," *Fuel*, vol. 87, pp. 3687-3693, 2008.
- 549 [13] C. Lee and C. Hwang, "An experimental study on the flame stability of LFG and
550 LFG-mixed fuels," *Fuel*, vol. 86, pp. 649-655, 2007.
- 551 [14] C. Hwang, S. Lee, J. Kim, and C. Lee, "An experimental study on flame stability and
552 pollutant emission in a cyclone jet hybrid combustor," *Applied Energy*, vol. 86, pp.
553 1154-1161, 2009.
- 554 [15] J. Ballester and T. Garcí'a-Armingol, "Diagnostic techniques for the monitoring and
555 control of practical flames," *Progress in Energy and Combustion Science*, vol. 36,
556 pp. 375-411, 2010.
- 557 [16] G. Lu, Y. Yan, and M. Colechin, "A digital imaging based multifunctional flame
558 monitoring system," *IEEE Transactions on Instrumentation and Measurement*, vol.
559 53, pp. 1152-1158, 2004.
- 560 [17] K. Kohse-Höinghaus, R. S. Barlow, M. Aldén, and J. Wolfrum, "Combustion at the
561 focus: laser diagnostics and control," *Proceedings of the Combustion Institute*, vol.
562 30, pp. 89-123, 2005.

- 563 [18] D. Sun, G. Lu, and Y. Yan, "An embedded imaging and signal processing system for
564 flame stability monitoring and characterisation," in *IEEE International Conference
565 on Imaging Systems and Techniques*, 2010, pp. 210-213.
- 566 [19] D. Sun, G. Lu, H. Zhou, and Y. Yan, "Flame stability monitoring and
567 characterization through digital imaging and spectral analysis," *Measurement
568 Science and Technology*, vol. 22, p. 114007, 2011.
- 569 [20] D. Sun, G. Lu, H. Zhou, X. Li, and Y. Yan, "A simple index based quantitative
570 assessment of flame stability," in *IEEE International Conference on Imaging
571 Systems and Techniques*, Beijing, China, 2013, pp. 190 - 193.
- 572 [21] Y. Huang, Y. Yan, G. Lu, and A. Reed, "On-line flicker measurement of gaseous
573 flames by images processing and spectral analysis," *Measurement Science and
574 Technology*, vol. 10, pp. 726-733, 1999.
- 575 [22] H. Cheng, X. Jiang, Y. Sun, and J. Wang, "Color image segmentation: advances and
576 prospects," *Pattern Recognition*, vol. 34, pp. 2259-2281, 2001.
- 577 [23] A. R. Jones, "Flame failure detection and modern boilers," *Journal of Physics E:
578 Scientific Instruments*, vol. 21, pp. 921-928, 1988.
- 579 [24] D. Sun, G. Lu, H. Zhou, and Y. Yan, "Measurement of soot temperature, emissivity
580 and concentration of a heavy-oil flame through pyrometric imaging," in *IEEE
581 International Conference on Instrumentation and Measurement Technology*, 2012,
582 pp. 1865-1869.

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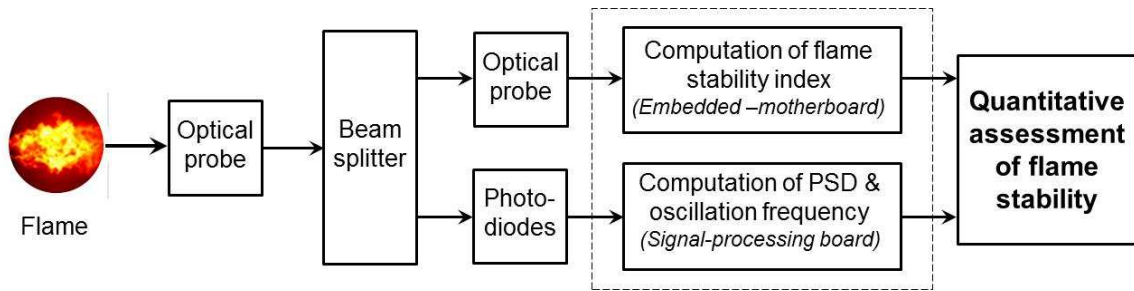
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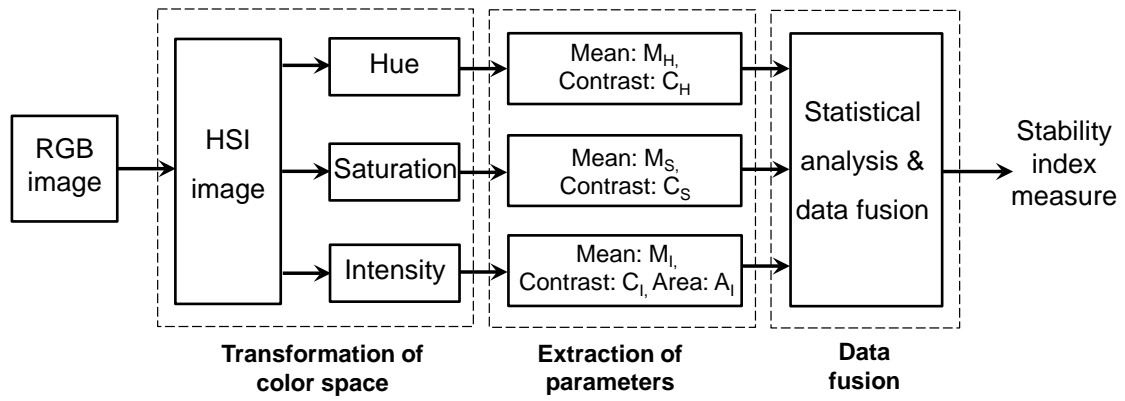
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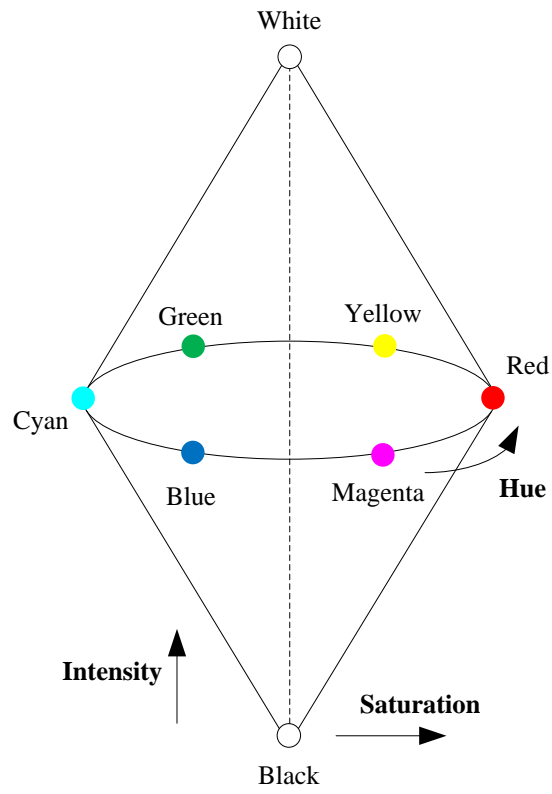
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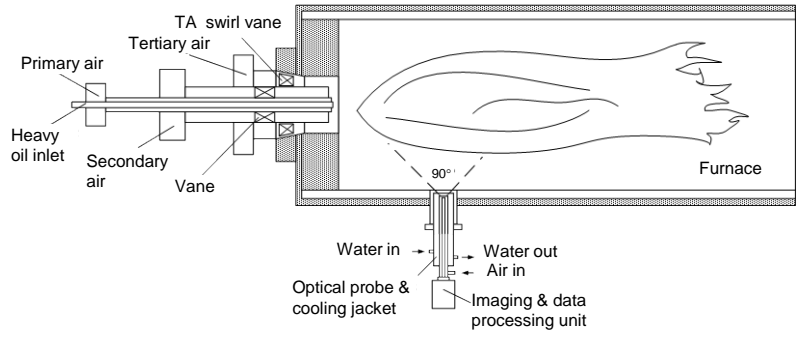
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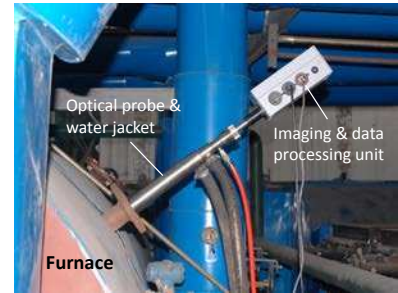
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Figure 4

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Figure 5

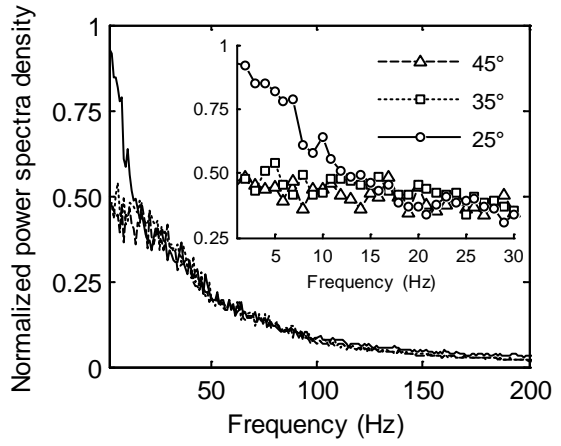
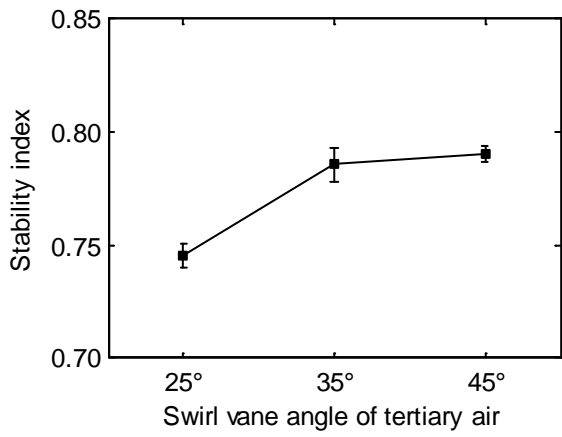
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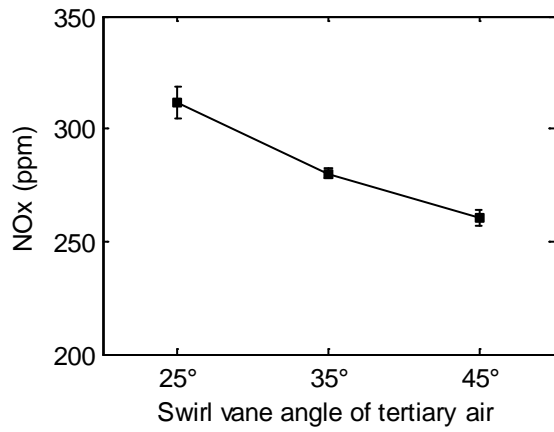
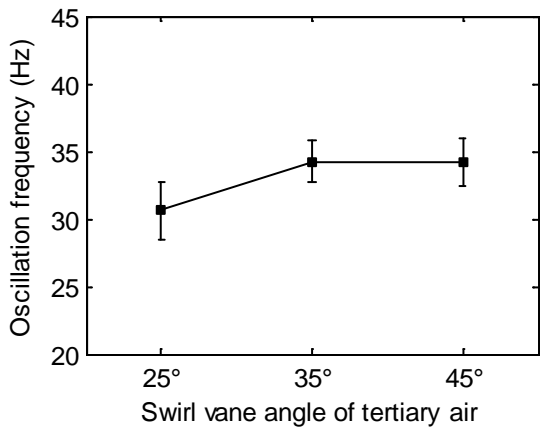
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Figure 6

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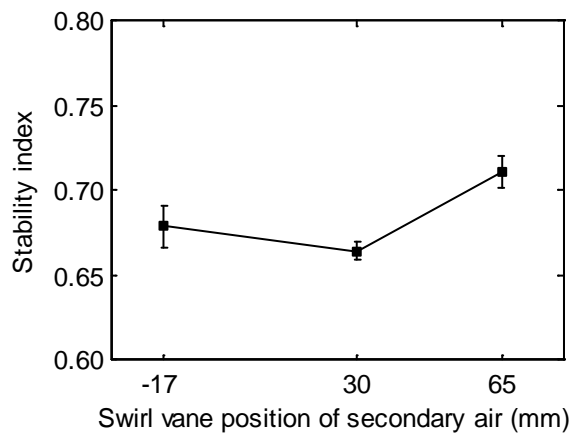
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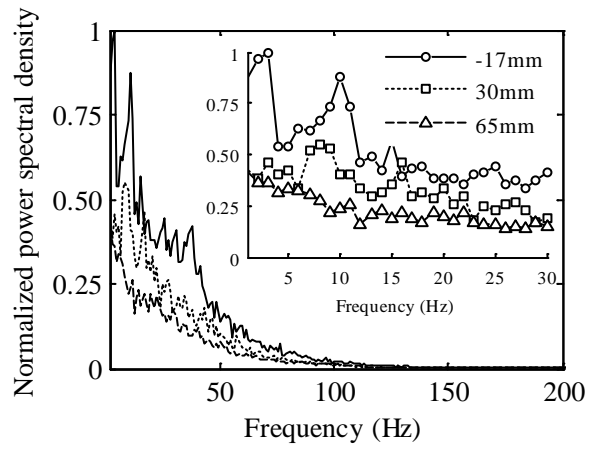


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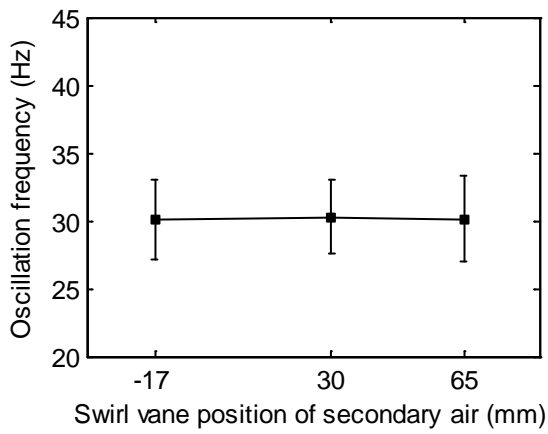
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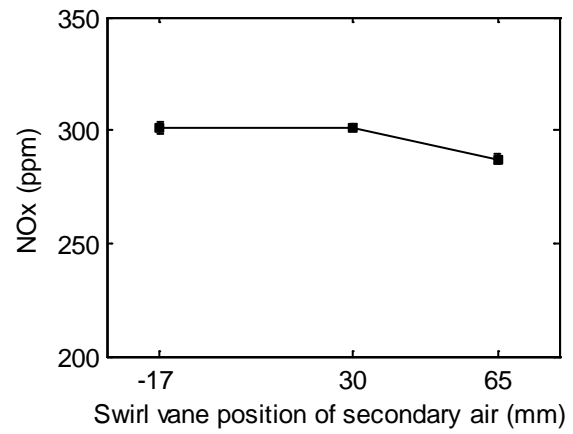


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Figure 8

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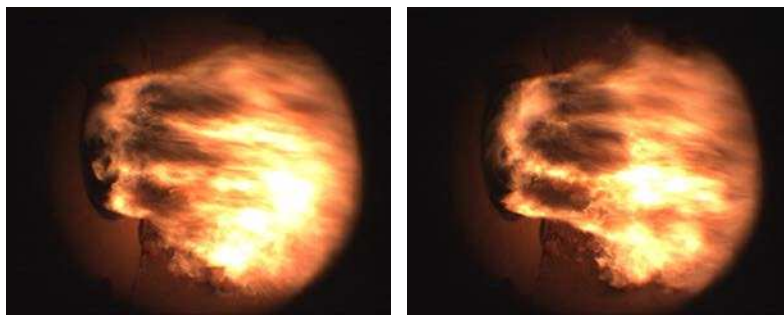
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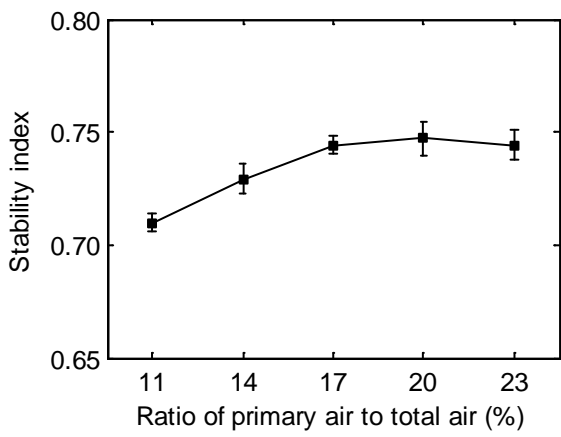
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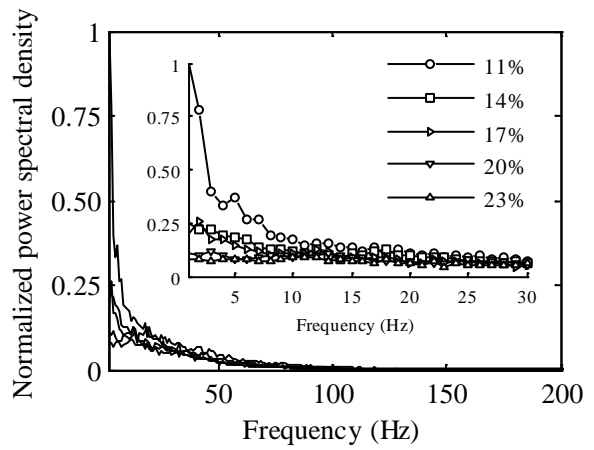


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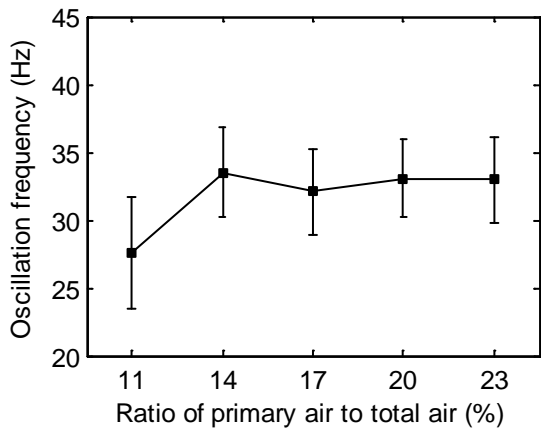
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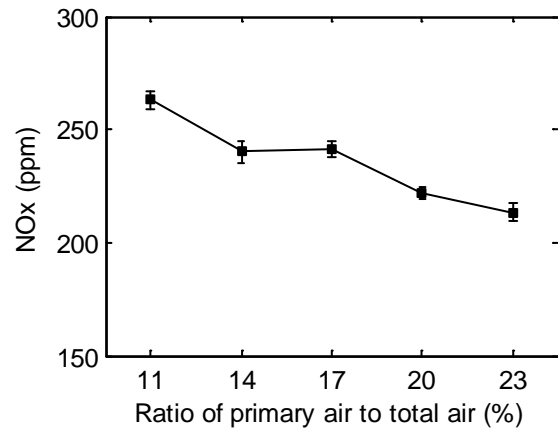
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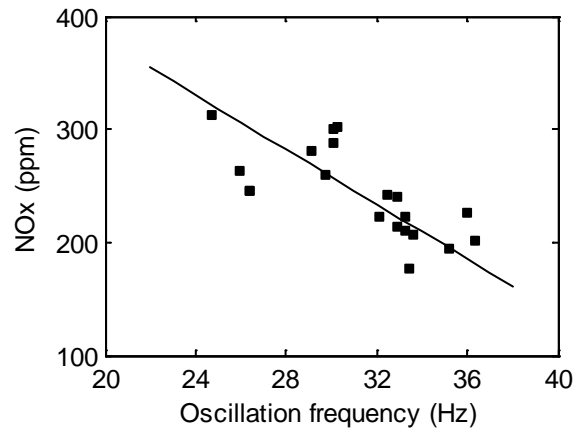
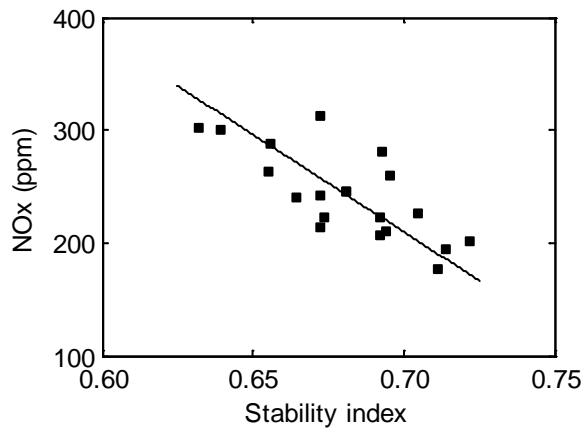
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Figure 10

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Figure 11