Experimental Assessment of the Acoustic Response of Laminar Premixed Bunsen Flames


Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands
Phone: +31- 402473819
Fax: +31- 402433445
e-mail: v.kornilov@tue.nl

Colloquium: Laminar Flames (13)

Paper length: total 5213 words (method 1).

Words equivalent lengths:

main text - 3878 words

equations – (6 equation +12 blank) lines x 7.6 words/line x 1 column = 137 words

nomenclature – 0

references – (20+4)lines x 7.6words/line = 183 words

figures:
fig. 1 – (30+10)mm x 2.2word/mm x 1column + 18words= 106words
fig. 2a – (30+10)mm x 2.2word/mm x 1column + 1word= 89words
fig. 2b – (34+10)mm x 2.2word/mm x 1column + 67words= 164words
fig. 3 – (49+10)mm x 2.2word/mm x 1column + 23words= 153words
fig. 4 – (55+10)mm x 2.2word/mm x 1column + 25words= 168words
fig. 5 – (55+10)mm x 2.2word/mm x 1column + 23words= 166words
fig. 6 – (55+10)mm x 2.2word/mm x 1column + 26words= 169words

figures total = 1015words

tables - 0
Abstract

The response of a premixed laminar conical flame to a periodic perturbation of the flow was analyzed. The idea was used to imitate the acoustic flow excitation by an oscillation of the flame anchoring ring. In this case the flow field is free from the ring vortices and other coherent structure formation typical for the harmonically excited jet pattern. Under this simplified perturbation condition the flame cone kinematics is studied and compared with the flame response to acoustic flow excitation. The heat release rate response Transfer Function (TF) for a foot-perturbed flame is measured and found to be close to a theoretical TF derived on the basis of the kinematical flame tracking approach (G-equation) for a uniformly oscillating flow. However, the TF of the jet perturbed flame deviates strongly from the TF of the anchoring ring perturbed flame and demonstrates a typical “constant time lag” behavior. A TiO$_2$ smoke tracing of the flow field shows the presence of a convective, sinuous perturbation of the flow core inside the flame cone when the flame is excited by the jet oscillation. In the case of the anchoring rim perturbed flame such a back influence of the perturbed flame on the upstream flow field is weak. Experiments when the flame’s anchoring rim oscillates in the transverse direction indicate that the flame base in-out radial motion can be a possible cause of the convective flow perturbation origin. The requirements for the extension of the kinematical type model of the flame response are formulated.

**Keywords:** Acoustic, anchoring rim, Transfer Function, premixed, Bunsen flame
1. Introduction

Laminar Bunsen type flames are widely used in practice of premixed gas fuel combustion in domestic and industrial burners. At the same time it is also a traditional and well-studied object in combustion science. These factors stimulate the research of acoustic instability of burners with Bunsen flames. It is often presumed that the relative simplicity of the flame allows understanding of the details of the flame with acoustic interaction and an application of this knowledge to more complicated flames. In spite of this apparent simplicity, the fluid dynamics of an acoustically excited jet is highly complex. After the jet release the flow velocity field is affected by the complicated structures of axisymmetric and streamwise vortices evolving in the jet shear layer. The size and strength of the vortices depend on flow, burner and perturbation parameters. The interaction of these coherent jet structures with the oscillating flame aggravates this situation even more. It would be advantageous if the oscillating flow field acting on the flame could be idealized and simplified. This is the purpose of this study.

An opportunity to imitate experimentally the interaction of the flame with uniform oscillating flow is based on the idea that the oscillation of the flame anchoring rim relative to a steady jet is equivalent to a uniform plane oscillation of the jet velocity relative to a motionless burner rim (flame attachment point). Therefore, by organizing burner rim oscillations, the flame cone kinematics under relatively simple excitation conditions can be studied. The comparison of the flame response to the attachment ring excitation and to the acoustic velocity perturbation of the jet reveals information about
the interaction of the flame with the more complicated non-uniform oscillating velocity field of an acoustically excited jet.

2. Experimental results and models of the flame response to flow perturbation; problem overview

From the beginning of studies of the Bunsen flames response to acoustic flow perturbation an essential discrepancy between experiments and theoretical results can be noted. Putnam’s experiments with many different systems where a self-sustained acoustic instability can be observed lead him to the conclusion that there is a combustion process time lag and that this time delay is equal to a traveling time of some gas particle from the burner outlet to the mean position in the flame zone [1]. By nature this time lag is a “system time delay”, in other words, the flame effectively responds to the flow perturbation some time \( \tau_0 \) after the flow perturbation is applied in the burner outlet. A first theory of the conical flame response to an acoustic flow excitation was developed by Merk [2] on a semi-phenomenological basis. He assumed that in response to a flow perturbation the flame heat release rate (flame surface area) tends to a corresponding stationary state with a rate proportional to the deviation between the current and the stationary value. This supposition naturally leads to a first-order equation for the temporal dynamics of the heat release rate. A characteristic time of the flame cone response was estimated as a mean residence time of a gas particle in the volume enclosed by the flame surface and burner orifice section. Not only the physical background of this estimation is obscure but, furthermore, the physical entity of this time is a system
relaxation time but not a system response time lag. A manifest discrepancy between experiment and theory is that for the high frequency limit the theory predicts a saturation of the phase delay $\phi$ between the flow velocity oscillation and the flame heat release rate response on a level of $\pi/2$. Experimental observations claim a linear growth of the phase delay with the frequency.

In the following decades a range of direct experimental measurements of the Bunsen type flame acoustic response were conducted and accordingly different empirical expressions for the flame Transfer Function (TF) were proposed (for an overview see Matsui [3]). Typically the TF is defined as the ratio of the relative flame heat release rate $Q'/Q_0$, to the relative flow velocity perturbation $V'/V_0$:

$$TF(f)=\frac{Q'(f)/Q_0}{V'(f)/V_0} \quad (1)$$

Here $f$ is the frequency of harmonic perturbation. If the flame burning velocity $S_L$ is constant over the flame surface area $A$ then $Q \sim A$ and the TF can be equivalently defined as

$$TF(f)=\frac{A'(f)/A_0}{V'(f)/V_0} \quad (1')$$

The results cited by Matsui [3] as well as last years’ measurements [4-7] definitely show the existence of a flame response time delay probably associated with some convectively traveling perturbation.

Significant progress in the theoretical analysis of the Bunsen flame acoustic response was stimulated when an idea of the flame front kinematical tracking (so-called G-equation
concept) was applied [8, 9]. An analytical expression for the flame surface area TF was derived and afterwards generalized and analyzed in [4, 10, 11]. For the case of a conical flame and a uniform one-dimensional acoustic perturbation of the fresh gas mixture velocity field: \( V(t,r) = V_0 + V' \cos(2\pi f t) \), \( U(t,r) = 0 \) (\( V \) is axial and \( U \) is radial velocity) the expression for the flame area response TF is given by [10]

\[
TF(f) = \frac{2}{\omega_*(f)^2} \left[ 1 + i\omega_*(f) - \exp(i\omega_*(f)) \right]
\]  

(2)

The reduced frequency \( \omega_* \) is referred to as the Strouhal number \( \omega_*(f) = 2\pi R/(S_L \cos(\beta)) = Sr(f) = (2\pi f H/V_0)[1 + (R/H)^2] \), \( R \), \( H \) and \( \beta \) are the burner radius, the flame cone height and the half angle at the flame tip [11].

The kinematical flame front tracking method allows to predict a perturbed flame form close to the experimentally measured one even in the case of cusped flames [12], but unfortunately the theoretical TF (expression (2)) has a qualitative behavior close to Merk’s first order TF. The phase of the TF as function of the excitation frequency is saturated on the level \( \pi/2 \) and the TF gain resembles a low-pass filter curve. Because these properties of the TF are in conflict with experimental observations a thorough analysis of the assumptions used in the derivation of expression (2) is necessary. Some of these assumptions are:

a- the flame propagation velocity is constant over the flame front and equal to the adiabatic flat flame propagation rate \( S_{L0} \);

b- the flame is anchored on the burner rim and the anchoring points are motionless;
c- the fresh gas velocity field is purely axial and uniform in space, there are no back influences of the flame on the velocity field upstream of the combustion front.

Larionov et al. [13] explain the deviation of the real TF from the theoretical one using the fact that $S_L$ in a region close to the burner rim is less than $S_{L0}$. The flame cone perturbations are originating from the flame anchoring point and next travel across the flame front towards the cone tip. The local heat release rate by a flame surface element $dA$ is proportional to the product $dQ \sim S_L \cdot dA$, consequently the maximal response of the flame heat release on a perturbation will be delayed in the time interval that the front form perturbation needs to cover the distance near the flame foot where $S_L < S_{L0}$.

The influence of the axial oscillation of the flame base point with some velocity amplitude has been studied theoretically in [11]. It is shown that, with exception of a minus sign difference, the flame TF is identical to the TF in the case when the flow velocity is perturbed - Eq. (2). The relative flame area fluctuation and accordingly the TF is the sum of the TF generated by the flow field and the flame anchoring point perturbation [11]. Therefore, the difference between the experimental TF and the TF given by expression (2) can’t be eliminated by just including into the model the axial flame anchoring point movement.

The modeled acoustic near field was included into the flame TF calculation by Lee and Lieuwen [11]. The effect of the burner tube opening as well as the influence of a flow velocity jump across the flame front was taken into account for the calculation of the acoustic velocity in all points along the flame. In a further development of this model [14] the influence of flame wrinkling on the flow field was also included. The flame TF calculated on the basis of this model is modified in comparison with the analytical TF.
(Eq. (2)). The phase of the TF as a function of frequency oscillates and tends to be saturated at some level between $\pi/2$ and $\pi$.

Another approach to include a more realistic flow field in the model was proposed by Baillot [12] and Schuller et al. [15]. The velocity field was experimentally measured, fitted and taken into account when the front kinematics was calculated. In the development of this idea [10,16] the flow model was prescribed in the form of a convective wave $V=V_0+V'\exp(iky-i2\pi f t)$ where a convective wavenumber $k$ is given by the mean flow velocity $k=(2\pi f)/V_0$. In [16] the velocity of a convective perturbation propagation was allowed to vary from the mean flow velocity $V_0$. The main result of these studies is that the flame TF calculated in the case where the flow field is prescribed in the form of a convectively (with mean flow velocity) traveling wave demonstrates the behavior typical for a system with a time lag. An analytically derived expression for the TF in this case is presented by Schuller et al. [10].

$$\text{TF}(f) = \frac{2}{\omega_*(f)^2} \frac{1}{1 - \cos^2 \beta} \left[ 1 - \exp(i\omega_*(f)) + \frac{\exp(i\omega_*(f)\cos^2 \beta) - 1}{\cos^2 \beta} \right]$$  \hspace{1cm} (3)

The TF modeled with the velocity field measured experimentally gives a better agreement with the experimental TF [10,15], but the question about the physical mechanism of the “traveling wave perturbation” origin is still open and needs to be studied. For a practical application, the velocity field measurement is a more difficult experimental task than a direct flame TF measurement.
3. The goal of this study

As it was mentioned before, from the point of view of flame cone kinematics the purely axial uniform periodic oscillation of fresh gas flow and the periodic axial oscillation of the flame attachment ring lead to an equivalent flame form oscillation and, accordingly, to a similar flame surface area TF (defined in Eq. (1′)) [11]. Using the method of flame anchoring point perturbation it is presumed to exclude (or weaken significantly) the excited jet coherent structure formation. Therefore, the flame kinematics effects can be detached and studied separately from the complicated jet flow effects.

In the frame of this research we will attempt to clarify the following questions:

- does the TF derived on the basis of the kinematical flame tracking approach (Eq. (2) or results presented in [4,9,10]) describe any real physical flame?
- what are the possible phenomena which lead to the difference between the theoretical and experimental TF?

  - can the effect of a reduced $S_L$ in the flame base zone explain the time delay behavior of the TF phase?
- what is the possible origin of traveling perturbation; is it a purely oscillating jet dynamic effect or is it a wrinkled flame back influence on the upstream velocity field or an effect related to the interaction of the perturbed jet with the flame?

The aim of this assessment is to formulate requirements for the models which should be included in the flame front tracking concept in order to predict the flame response on the
acoustic perturbation and to get the TF which catch the main features of the experimental TF.

4. Experimental Methods and Setups

A conical flame stabilised in a premixed methane-air mixture was situated on a cylindrical burner (Fig. 1a) with a convergent nozzle that provides a top-hat mean velocity profile. The burner vessel height is ~15cm and its diameter is 7 cm. The acoustic pure tone forcing of the flow was organised via a loudspeaker installed upstream of the burner in the mixture supply line. To implement the flame anchoring point oscillation, the flame was attached to an oscillated ring-shaped flame holder (1 in Fig. 1b) installed approximately 0.5 mm above the nozzle rim. The ring with an internal diameter equal to the burner internal diameter (1 cm) was manufactured from 0.25 mm diameter wire and mounted into a thin ceramic tube (2) of 7 cm long. This flame holder was oscillated by an electro-dynamical deflector (3).

Experimental measurements of the flame TF and jet flow visualization were conducted. As a heat release rate indicator the chemiluminescence intensity of OH* was chosen [17]. The gas flow rate $V_0$ and equivalent ratio $\Phi$ were operated by mass-flow controllers. For the flow velocity oscillation monitoring a hot-wire anemometer was used. A probe wire was installed across the burner tube at a distance ~0.5-1 cm from the burner rim. Based on a response linearity check, a perturbation amplitude $V'/V_0 \sim 8\text{-}10\%$ was chosen. For the monitoring of the flame anchoring ring oscillation, an additional optical scheme was developed (Fig.1b). An image of a lamp spiral (4) is formed by a lens (5) on a small
screen (6) fixed on the ceramic ring holder close to the ring (flame). In a stationary holder position, approximately half of the lamp spiral image is blocked by the screen. The oscillation of the ring leads to a modulation of the blocked image portion and accordingly to a modulation of the light intensity that falls onto the photodiode (7). The amplitude of the ring oscillation was chosen approximately equal to the wire diameter (0.25mm). This value is in accordance with the flame end point motion amplitude when the acoustic flow excitation is applied and leads to a same order of magnitude of the flame form modulation when the flow velocity perturbation is \( V' \sim 0.1V_0 \). More detail about the TF measurement can be found in [6, 7].

Raw experimental data consist of 0.5 s time samples of the excitation \( (V'(t)) \) or flame holder motion \( X(t) \) and the \( I_{OH^*}(t) \) time history digitized with a sampling rate of 20 KHz. The gain of the TF was calculated as the ratio of the amplitude of the Fourier transform of the \( I_{OH^*}(t) \) signal (integrated over the excitation frequency peak) and the amplitude of the Fourier transform of the perturbation velocity signal. The phase difference between \( I_{OH^*}(t) \) and the velocity excitation was restored by cross-correlation analysis of these signals. For the ring perturbed flame, the TF phase was recalculated as a phase lag between the \( I_{OH^*} \) and an equivalent jet velocity oscillation relative to the motionless ring. For this purpose we used the relation \( V'(t) = - \frac{dX(t)}{dt} \). In the case of harmonic perturbation it gives a factor \( 1/(2\pi f) \) for the amplitude relation and leads to a phase shift \( \pi/2 \) between \( V'(t) \) and \( X(t) \) and allows to avoid the differentiation of noisy signal.

To visualize the flow the TiO\(_2\) smoke trace technique was applied. Small jets of air with TiCl\(_4\) vapor were injected in the flow and due to the reaction of TiCl\(_4\) with air moisture
nanosize TiO$_2$ particles smoke are formed. Smoke traces were illuminated by a light sheet of a Nd:YAG pulsed laser synchronized with the CCD camera.

5. Flame Transfer Function

5.1 The TF of acoustically perturbed flame

An extensive parametric investigation of the TF of the conical premixed lean laminar flame where the flow velocity was acoustically perturbed was conducted previously. It includes the study of the influence of the mean velocity $V_0$, equivalence ratio $\Phi$, mean velocity profile (Poiseuille and top-hat), burner neck diameter $d$, burner tube wall thickness, tube material, burner opening geometry [6,7]. A summary of the results follows:

- The flame heat release transfer function has a particular dependence on the frequency. It exhibits the behaviour typical for a system with a time delay and for a system with a low-pass filter. Some additional effects lead to a small but weakly frequency dependent part of the TF. Figs. 2a and 2b (lines 1) present a graph of the typical TF gain and phase in the case when the jet velocity is perturbed.

- The TF can be described in a universal phenomenological form with a few (fitting) parameters [6,7]

\[
TF(f) = \frac{\exp(-i\tau_0 \cdot 2\pi f)}{(i\tau_1 f + 1)^2 + A} \cdot \frac{1}{(A + 1)}
\]  

(4)
Here $\tau_0$, $\tau_1$, $|A|$, $\arg(A)$ are fitting parameters. The factor $1/(A+1)$ is added to satisfy the physical limit $TF(f \to 0) = 1$.

- The TF has a response “time delay” part described in (4) by the factor $\exp(-i\tau_0 f)$. The value of time delay $\tau_0$ can be obtained via a fit of the experimental points by expression (4). There is a universal relation between the time lag $\tau_0$, the gas velocity $V_0$ and the flame height $H$ [6,7].

$$T_0 = \frac{(2\pi\tau_0 V_0)}{H} = \text{const} \quad (5)$$

The $T_0$ in (5) is independent from $V_0$, $\Phi$, $d$, but it varies with mean velocity profile ($T_0 \approx 4.4(\pm 0.2)$ in case of a parabolic profile of $V_0$ and $T_0 \approx 5.4(\pm 0.25)$ in case of a flat profile).

The theoretical phase of the TF derived in the frame of the “convectively travelling wave” model (Eq. (3)) is presented in Fig. 2b by line 4. The theoretical phase overpredicts the value of the measured one. In the high frequency limit the phase of the TF (3) is equal to $\phi = \omega - \pi/2$ [10] which gives the value $T_0 = 2\pi$ somewhat larger than the experimental value ~5. However, qualitatively the time lag behaviour of the experimental TF is captured by model (3).

5.2 The TF of flame with axially perturbed anchoring points

Typical curves of the experimentally measured TF of the flame when the flame holder ring axial position is periodically excited are also presented in Fig. 2. The gain of the TF
(line 2 in the Fig. 2a) resembles the gain of the TF for the flame with a perturbed flow, but the phase (line 2 in the Fig. 2b) does not demonstrate the typical “constant time delay” behaviour of line 1 in the same figure. The phase as a function of frequency oscillates and tends to be saturated in the range between $\pi/2$ and $\pi$. Evidently the curve of the TF for the base perturbed flame is more close to the ones of the theoretical TF (Eq. (2), curves 3 in Figs. 2a and 2b).

In order to clarify the cause of the difference between the anchoring point perturbed and flow velocity perturbed TF different flame and flow visualisation experiments were conducted.

6. Oscillated Flames Form and Flow Field Visualization

Fig. 3 presents a comparison of the flame front shapes in case of the perturbed flow velocity (left) and perturbed flame anchoring ring (right). The perturbed flame forms are identical and both look like a sinuous perturbation traveling toward the flame tip. The only visible difference of the flame front movement can be marked close to the anchoring point. In case of the ring perturbed flame the flame end point moves up and down together with the ring while in the jet perturbed case some additional “in-out” radial movement of the flame end point can be observed.

The flow field patterns which correspond to the two types of flame perturbation are significantly different. In the flame holder perturbed case the flow core is uniform as in the case of a cold jet perturbation (no flame) as well as when the flame is ignited. The
streak lines in Figs. 4a and b are straight and only a weak flow perturbation close to the oscillating ring and close to flame front can be recognized. In the experiments when the jet velocity was acoustically perturbed the well-known phenomenon of a ring vortex formation in a shear layer of the jet is observed – Fig. 5a. The size of the ring vortices varies depending on the excitation frequency. A higher frequency corresponds to smaller vortices and, accordingly, to a less perturbed core of the jet. When the flame is ignited, the vortex structure can’t be distinguished anymore. However, the TiO₂ smoke streaks inside the flame cone are curved, clearly indicating that the jet flow core is perturbed. This perturbation is of the varicose type (cylindrically symmetrical) and it was first observed by Markstein, [18]. Quantitative LDV measurements of the acoustically perturbed cold jet and the flow inside the flame cone [19,20] are in agreement with this visualization result.

7. Discussion

Because in the cases of gas jet and flame holder perturbation the flame kinematics (oscillating flame front form) is similar, the effects related to a non-constant S_L can’t be the main reason of the TF time lag behavior. The decrease of S_L close to the anchoring point as well as the rise of S_L in the flame tip region should be the same in these two cases, but the TF phase characters are dramatically different. The similarity of the flame forms is a plausible cause of the similarity of the TF gain (lines 1 and 2 in Fig. 2a). The difference of the flow field in the oscillating jet core for the cold jet and the flow inside the flame cone signifies the importance of the flame back influence on the
upstream flow field. However, because such a feed-back is not observed in the case of the anchoring ring perturbed flame the oscillating flame form alone can not explain the upstream flow core modification by the flame. 

The evident difference of flame motion between the cases of jet and ring perturbed flame is the radial in-out motion of flame foot zone when the flow velocity is excited. The rim formed by the flame anchoring points periodically contracts and releases the flow. This is the probable cause of the peristaltic flow modulation. In order to check this hypothesis an experiment with a periodic radial flame holder oscillation is desirable, but such a modulation is difficult to realize experimentally. A periodic oscillation of the flame holder ring in the horizontal direction leads to an asymmetrical flame perturbation, but in the diameter section which is parallel to the ring oscillation direction such a perturbation stimulates the flame anchoring point in-out movement. Visualization of the cold flow and the flow with the flame shows that the transversal flame anchoring point oscillation does not perturb the cold jet core (Fig. 6a), but leads to a sinuous perturbation of the jet flow inside the flame cone (Fig. 6b). The TF phase delay of the flame response to the transversal flame holder perturbation shows a typical “constant time delay” behavior – line 5 in Fig. 2b. (Because of the antisymmetric flame front perturbation the OH* signal should be measured from the half of flame.) These observations indicate that the flame anchoring point’s radial (in-out) motion is one of the key points of the oscillating flame back influence on the oscillated flow field. 

8. Conclusions
Today’s G-equation based theoretical description of the flame response to a periodical perturbation predicts the TF of a flame anchored on an oscillated flame holder with a reasonable accuracy. The plausible reason for the large deviation between the flame response to jet velocity perturbation and flame holder excitation is the difference of excited flow pattern and the back influence of the flame on the upstream flow field. The peculiarities of the flame base oscillation play an important role in the formation of the flame back influence on the upstream flow.

The results presented in this paper indicate that in order to simulate successfully the flame response on acoustic flow perturbations such models should include:

- a model for the oscillating flow field including the fluid motion in the shear layer region;
- an adequate model for the flame anchoring mechanism which allows to catch the flame anchoring point motion;
- a model for the back influence of the gas expansion in the flame on the upstream flow field.

**Acknowledgements**

This research is supported by the Technology Foundation STW, applied science division of NWO and the technology programme of the Ministry of Economic Affairs.
References


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Fig. 1
Experimental setup. a- Bunsen burner, b- scheme of the monitoring of the flame holder ring oscillation.

Colour figure in electronic version only.

Fig. 2
The transfer function gain (a) and phase delay (b) of the flame response to the jet velocity perturbation (curves 1) and flame holder oscillation (in jet direction - curve 2, in transversal direction – curve 5 ). Theoretical TF derived in frame of the uniform velocity perturbation (Eq. (2)) – curves 3 and the TF derived in frame of the travelling wave model (Eq. (3)) – curves 4. \( V_0 = 165 \text{cm/s}, \phi = 0.85. \)

Colour figure in electronic version only.

Fig. 3
Comparison of the oscillated flame form under the flow velocity excitation (right) and flame holder ring oscillation (left). \( V_0 = 130 \text{cm/s}, \phi = 1.2, f = 200 \text{Hz}. \)

Fig. 4
TiO\(_2\) visualization of the flow field perturbed by oscillated ring.

a- cold jet (no flame)
b- flow with the flame

\( V_0 = 130 \text{cm/s}, \phi = 1.2, f = 200 \text{Hz}. \)
Fig. 5

TiO$_2$ visualization of the acoustically perturbed flow field.

a- cold jet (no flame)
b- flow with the flame

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Fig. 6

TiO$_2$ visualization of the flow by transversally oscillating flame holder ring

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b- flow with the flame

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![Fig. 1](image1.png)

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![Fig. 2](image2.png)
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Fig. 6

TiO$_2$ visualization of the flow by transversally oscillating flame holder ring

c- cold jet (no flame)

d- flow with the flame

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