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Evaluation of Statistics and Spatial Correlations on Planar Distribution of Gaseous Mixing in a Turbulent Recirculation Flow Field

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Abstrak

Teknik visualisasi aliran yang berdasarkan pada lembaran laser dan kuantifikasi dari intensitas sinar dari pependaran Mie telah dapat digunakan dengan baik untuk mengevaluasi statistik dan korelasi spatial dari distribusi gas yang diinjeksikan ke dalam medan aliran udara turbulen bersirkulasi dengan konfigurasi tangga. Dalam eksperimen kecepatan aliran bebas diatur pada, $U_o = 10$ *m/s dan ketinggian tangga ditetapkan sebesar,* $H = 20$ *mm. Kajian berfokus pada karakter fluktuasi dan distribusi gas di dalam zona resirkulasi dengan tujuan mengungkapkan karakteristik percampuran gas injeksi dengan udara. Hasil-hasil menunjukkan bahwa distribusi dari gas yang diinjeksikan memperlihatkan kecenderungan yang berbeda yang tergantung pada lokasi injeksi. Apabila momentum spesifik injeksi ditingkatkan level fluktuasi maksimum dari konstrasi gas berkurang. Suatu pengurangan sampai 30% dari nilai RMS maksimum dari fluktuasi intensitas luminasi dapat teramati apabila rasio momentum spesifik dari injeksi dittingkatkan dari 0,04 sampai 0,3. Korelasi spatial menunjukkan bahwa percampuran antara gas injeksi dengan udara di sekelilingnya berlangsung lebih cepat dan lebih baik dalam hal injeksi dilakukan di dekan titik pertautan kembali karena turbulensi yang lebih besar di region tersebut.*

Keywords: *Aliran resirkulasi, Visualisasi aliran, Percampuran gas, Distribusi planar dan Korelasi spatial.*

Abstract

A powerful flow visualization based on a laser-sheet and the quantification of the intensity of the light from Mie scattering had been introduced and successfully used to evaluate the statistics and spatial correlations of gas distribution injected into a two-dimensional turbulent recirculation airflow, utilizing a backstep configuration. In the experiment the free stream velocity was, $U_o = 10$ *m/s and the step height was,* $H = 20$ *mm. The study focussed on the fluctuation and the gas distribution in the recirculation zone in order to elucidate the gas-air mixing characteristics. The results show that the distribution of injected gas shows different trends depending on the location of injection. When the specific momentum of injection is increased, the maximum fluctuation level of the gas concentration decreases. A reduction up to 30 % of the maximum RMS value of luminance intensity fluctuation can be observed when increasing specific momentum ratio of injection from 0.04 to 0.3. Spatial correlations suggested that mixing between injected gas and surrounding air was more rapid and better in case injection in the near reattachment point due to higher turbulence in the region.*

Keywords: *Recirculation flow, Flow visualization, Gaseous mixing, Planar distribution, Spatial correlation*

1. Introduction

Practical design problems of a flame holder in a combustor have increased the need to better understand the mixing process between the injected fuel and the surrounding air. Even in the absence of chemical reaction, the mixing process itself has been a complex process, which is controlled by a coupling of convective mass transfer and diffusion mechanism and it is very much influenced by the flow structure involved. A two-dimensional recirculation flow such those produced by a bluff-body, a V-gutter or a back step had been widely proposed as prefered flow field structure to fulfill the requirement for flame holding. Although the complexities of a recirculation flow has been investigated by many researchers, most of the published works deal with the case of no mass addition and mainly feature some aspects related to the flow structure and dynamic as well as the heat transfer characteristic [1-3]. Comparatively limited studies have been conducted in the case where mass bleed was issued to the flow field. Among of them, Yang et al.[4-5] investigated a back-step flow with mass addition from porous plate. Later, Yang and Kuo [6] had also done numerical analysis confronting the experimental data of Yang et al.[5] Results from those studies showed that mass addition altered the mean flow field, the turbulence features as well as the heat transfer characteristics in the whole recirculation zone. De Groot et al. [7-8] utilized a Rayleigh scattering technique to measure the species concentration of bleed flow (cold and with combustion) from the porous floor behind the step, and found that molecular mixing in the recirculation zone was excellent, and the measured bleed gas concentration profiles agreed to those predicted using a modified κ-ε model by Richardson et al. [9] Other experimental work of Haibel and Mayinger [10] investigated the effect of injection geometry to the cold and reactive mixing of gas injected into a high-speed air stream with the existence of a step by holographic interferometer visualization. Their results showed that the development of the mixing jet could be predicted with their proposed formula. However, in the aforementioned works, no comprehensive discussion on the distribution of the injected gas within the recirculation zone, and hence the mixing process has not been thoroughly clarified. An obvious reason for this lack stems from the difficulties to conduct a spatial and temporal-resolved non-contact assessment of the complex process that occurs in such flow field.

Motivated by the need of a better understanding focussed exclusively on the gas-air mixing in a recirculation flow field, this work introduces a less complicated but powerful enough experimental technique to assess the mixing of non reactive nitrogen gas injected to the backward facing-step air flow field. Here, the injected gas distribution in the recirculation zone is investigated by means of laser-sheet based tomography using Mie scattering of silicon oil droplet method, where the scattered light intensity is captured by a high-speed video visualization and then quantified. Thereby, considering nearly uniform size of particles seeded in the injected gas, the luminance intensity of scattered light from seeded nitrogen gas is regarded as a direct measure of the nitrogen concentration distribution inside the mixing region. The distinctive merit of the method is that without much complexities on the optics, it can reveal detail information on the planar gas distribution with good spatial and sufficient temporal resolution so that major features of how the injected gas behave as it enters the flow field can be observed. To encounter the relevance of practical concerns in a combustor design, the injection location as well as the specific momentum of injection was chosen as the parameter of interest, and their values were varied. Then, descriptive statistics of the obtained data are discussed comprehensively in order to elucidate the mixing process between the injected gas and the surrounding air flow with respect to the growth, penetration, fluctuation and relative concentration distribution of the injected gas within the recirculation zone.

2. Experimental Method

2.1. Experimental Apparatus and Instrumentation

A schematic of the experimental apparatus for the present study is sketched in Fig. 1. The experiment was conducted in a horizontal small-scale open loop wind tunnel. Airflow was supplied from a vortex blower and passed through an orifice manometer system to maintain a constant flow rate over extensive period of time. The dimensions of test section were 50 x 80-mm2 cross section upstream of the step, and length of 300 mm downstream of a 20 mm-height step (H). The base wall of test section was installed with a gas injection port with 1 mm-width slit exit spanned across the test section at a distance l_f from the step. The coordinate system was set as seen in the figure.

Nitrogen gas was issued upward to the test section after passing through a particle seeding system to provide light scattering particles. This particle seeding system played a critical importance in the present study since all the analysis would be based on recorded images. For this purpose, the present work used similar system to that of Ueda et al. [11] Dimethyl Silicon oil (Toshiba Silicon, TSF 451-50), with kinematic viscosity ν = 50 mm2/s, density ρ = 0.91265 g/ml and boiling point T_b □ 300 oC was used as particle source. Oil droplets were produced by using an arrangement of atomizers (PENICILIN Nebulizer). Number of atomizers through which nitrogen flow passed was regulated to produce a constant seeding. This kind of particle seeding system has been previously proved by phase Doppler particle sizing technique [12] to generate droplet particles with quite uniform diameter (1~2 μm) and number of density (□ 400 particles/cm3).

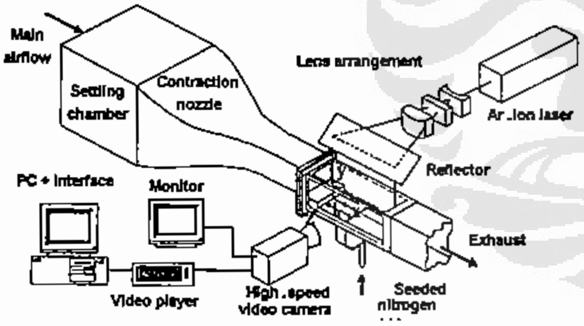


Figure 1.
Experimental Set-up

Visualization instruments consist of an argon ion laser (Coherrent Innova 70-4: 4 W, 514.5 nm), a high-speed video camera (Motion Scope HR Series, shutter speed 1/2000 s, 1000 fps) and cylindrical lens arrangement. A 0.4 mm-thickness, 100 mm-width laser sheet was made in the plane of visualization. Recorded images were then transmitted to a personal computer for further analysis. To suppress the background light effect, image recording was done in a dark room condition.

2.2. Assessment of Gas Distribution by Measurement of Scattered Light Intensity

For analyzing the video images, software was developed to recognize the luminance intensity on the image. Figure 2 shows region and method of determining luminance intensity on such an image.

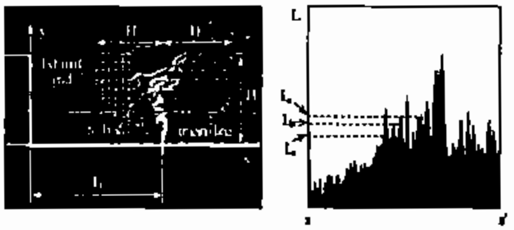


Figure 2.
Assessment Method of Luminance Intensity

A luminance intensity (L) profile could be obtained along a corresponding tracing line (ss') which position could be freely varied. The measurement that respect to the relative concentration distribution of injected nitrogen gas was done by directly measuring the luminance intensity value on the image at grid points of 1 x 1 mm^2 mesh in the region between 1.0 H upstream and downstream of injection location, from y/H = 0.1 to 1 for vertical plane images, and from z/H = –1.5 H to +1.5 H in span-wise direction for horizontal plane images.

Normally luminance intensity data from 2048 frames were measured for each parameter condition. The obtained data included infrequent but not negligible erratic values, which might be originated from sources, such as the existence of droplet particles whose size much larger/smaller from average particle size, image noise produced in video capturing process, and so on. These spurious data were reduced by 6σ method. The remaining data were then used to calculate statistical values of the quantity of interest. The corresponding estimated statistical uncertainties ± 0.7 % for mean luminance intensity and ± 1.1 % for RMS of luminance intensity fluctuation. The details of 6σ method for data reduction and determination of statistical uncertainties were described in the reference [12], with proper change of the symbol of measured quantity.

2.3. Experimental Condition

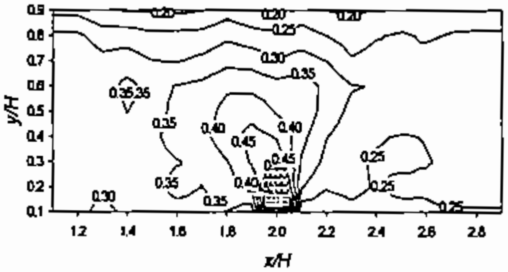
Over the entire experimental conditions, the main air flow velocity ahead of the step was maintained constant at U_o = 10 m/s. Preliminary velocity measurement using LDV to determine initial upstream condition and location of reattachment point showed that the main flow upstream of the step was uniform with turbulence intensity about 0.7 percent. The boundary layer just upstream of the step edge was having a maximum turbulence intensity around 3 percent. The thickness of the boundary layer before the separation point was 3 mm (0.15 H). The distance from the step to the reattachment point x_r, defined as location with zero mean horizontal velocity at 0.05H above the wall was 5.5 H. The principal parameters of the experiment were the ratio of specific momentum between the injected nitrogen gas and main air flow ($I=\rho_{N2}V_{N2}^2 / \rho_{air}U_o^2$) and the streamwise distance from the step to the injection port (l_j). The specific momentum ratio was varied (I = 0.04, 0.1, 0.3, and 0.5) by altering Nitrogen injection velocity (V_{N2} = 2, 3.2, 5.6, and 7.2 m/s) at constant main airflow. Two cases of gas injection location within recirculation region where regime of the flow was different were selected. One located at near step region (l_j/H = 2) where recirculating flow dominated the region, and another one located at near reattachment point (l_j/H = 4) where shear turbulence was predominant. The visualizations were done at vertical center plane (z/H = 0), and horizontal planes for several heights (y/H = 0.1 ~ 1).

3. Results and Discussion

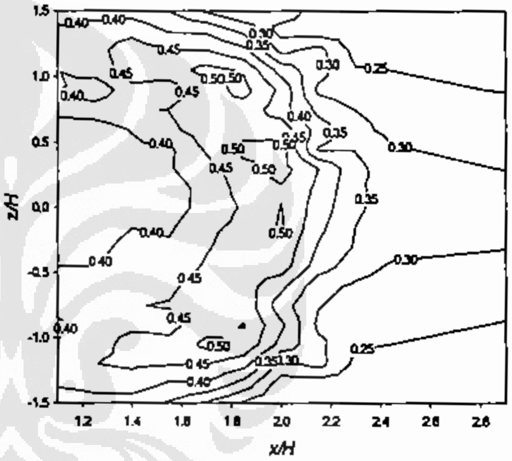
3.3. Statistics of Injected Gas Distribution

3.3.1. Mean Contours

Figure 3 shows contours of mean intensity of scattered light in case nitrogen issued from location near the step (l_j/H = 2) for specific momentum ratio I = 0.04. The luminance intensity has been corrected from background luminance and is presented as a normalized value to the mean intensity of the scattered light taken at position 1 mm (0.05 H) above the exit of injection port (L_o), where the concentration of injected gas is considered as maximum.



(a) $z/H = 0$



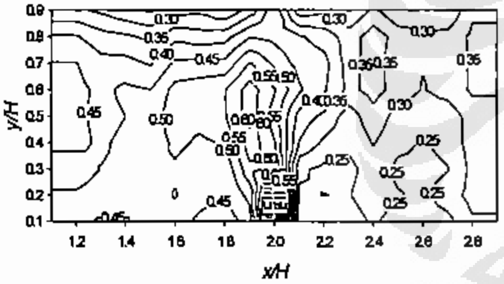
(b) $y/H = 0.3$

Figure 3.
Contours of Mean Luminance Intensity with injection at l_j/H=2; I= 0.04
(contour interval 0.05)

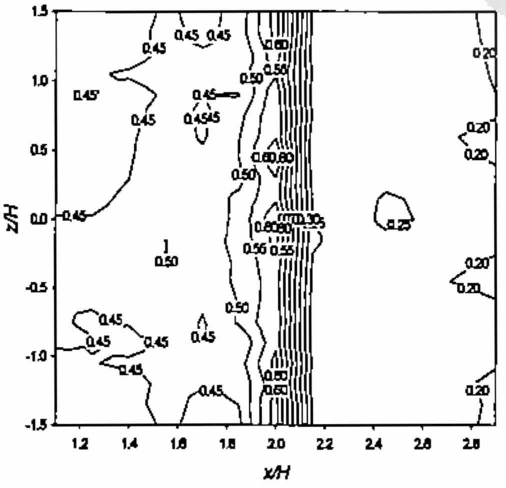
At the center vertical plane, Fig. 3(a) indicates that high mean concentration of the nitrogen gas decreases rapidly as the relative intensity L/L_o values 0.5 only at a distance about y/H = 0.25 H from injection point. The gradient in cross stream direction ($\partial[L/L_o]/\partial[y/H]$) is steep, as represented by close interval between isoluminance lines in the region. This indicates the strong influence of the cross flow effect from local reverse airflow velocity that tends to suppress upward growth. Further upward (y/H > 0.25), the mean concentration of the injected gas decreases more slowly as the intensity gradient ($\partial[L/L_o]/\partial[y/H]$) is lower.

The attenuation on the change of concentration gradient is likely due to shear turbulence, which come into effect and make more effective mixing. Furthermore, Figs. 3(b) show the evolution of spanwise distribution of injected gas at the plane of $y/H = 0.3$. The distribution is symmetrical about $z/H = 0$ and dominated by curved isoluminance lines which indicates only a slightly concentration decrease in spanwise direction up to region $z/H = \pm 0.8$, as the L/L_0 value varies only 10 percent from the center value. The pattern also indicates that there formed two similar structures which are symmetrically separated along the plane of symmetry which principally led by the three-dimensional growth of the injected gas trajectory.

Meanwhile for the case of $I = 0.3$, the picture of gas distribution is different as shown in Fig. 4(a). High concentration region of injected gas penetrates deeper. The relative intensity L/L_0 reaches 0.5 at the shear layer region about $y/H = 0.7$. The gas jet can overcome cross flow effect from local reverse flow. A difference of quite significance value of L/L_0 up to 0.15 can be observed between the regions upstream and downstream of injection point. The difference is an indication that the recirculating flow region splits into two. The injected gas distributes more toward upstream recirculation zone as the convective mass transfer is enhanced toward this region. On the other hand, the distribution of the gas toward the downstream recirculating zone is apparently retarded as indicated by lower mean value of L/L_0 and a steeper gradient ($\partial[L/Lo]/\partial[x/H]$) along the downstream side boundary of the jet. Furthermore, Figs. 4(b) show that the injected gas distributes without remarkable concentration gradient in spanwise direction.

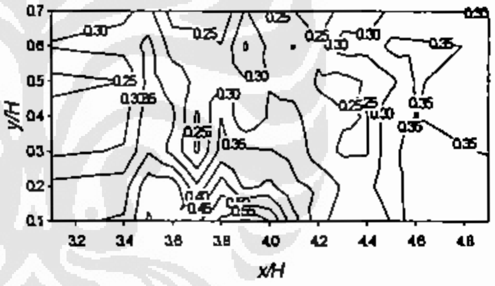


(a) $z/H = 0$

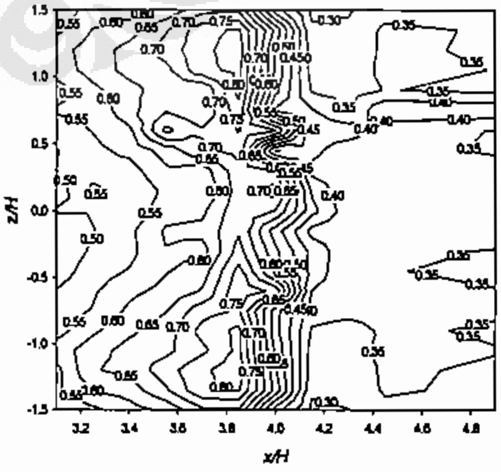


(b) $y/H = 0.3$

Figure 4.
Contours of Mean Luminance Intensity with injection at l/H=2; I= 0.3(contour interval 0.05)



(a) $z/H = 0$



(b) $y/H = 0.3$

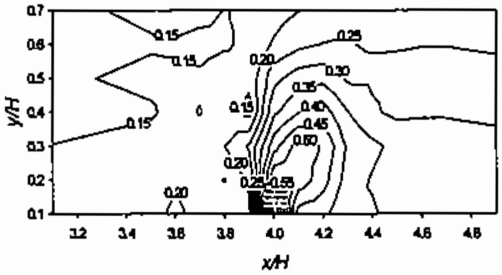
Figure 5.
Contours of Mean Luminance Intensity with injection at l/H=4; I= 0.04
(contour interval 0.05)

Figure 5 (a) show contours of mean L/L_0 in the case of $l/H = 4$. Contours of $I = 0.04$ show that the mean L/L_0 decreased to 0.5 within a small vertical distance of $y/H = 0.15$. The gas distributes mostly toward upstream region due to reverse flow with higher velocity and region $L/Lo > 0.5$ is confined in the recirculating zone at a narrow vertical between the base wall and shear. This suggests that mixing in this region is rapid and intense which is mainly controlled by strong shear turbulence. Moreover, observation on Figs. 5(b) show similar trend to the case of $l/H = 2$ on Figs. 3(b), regarding the spanwise characteristics of the gas distribution

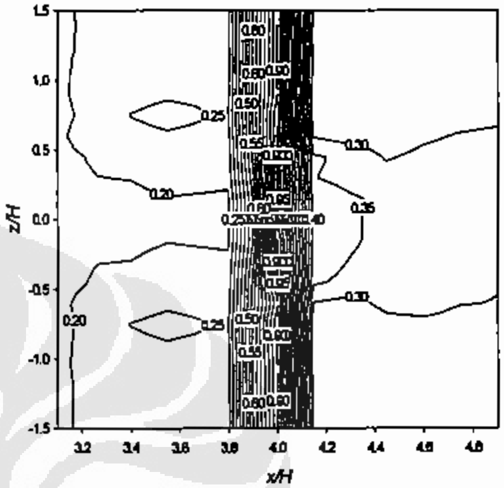
Meanwhile in the case of $I = 0.3$, Fig. 6(a) indicates the formation of two regions of recirculating flow upstream and downstream of injection point, similar to the case of $l/H = 2$ with the same injection momentum. However, an opposite trend of gas distribution can be seen due to the difference of initial thickness of the recirculation zone and the shear layer above the injection point as well as the penetration depth of the injected gas. The value of L/L_0 implies that the injected gas penetrates deeply through the shear layer up to the region where free stream comes into effect. Most part of the injected gas flows and reentrains into the recirculating zone downstream of the injection point, as L/L_0 is higher in this region. Lower L/L_0 and steeper gradient ($\partial[L/L_0]/\partial[x/H]$) along the upstream side of jet boundary suggests that only a very little part of the gas distributes toward recirculation zone upstream of the injection point. Further, Figs. 6(b) confirm the two-dimensionality of the injected gas distribution, as no remarkable variation of L/L_0 are observed in spanwise direction at every plane height.

3.3.2. RMS Contours

Contours of RMS of intensity fluctuation in case the nitrogen gas is issued at $l/H = 2$ are presented in Figs. 7 for $I = 0.04$.



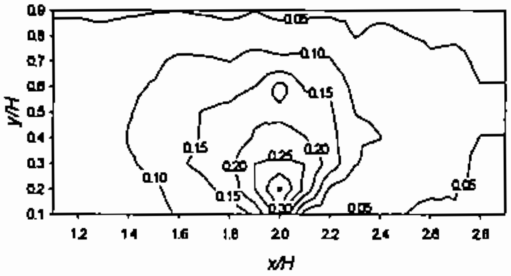
(a) $z/H = 0$



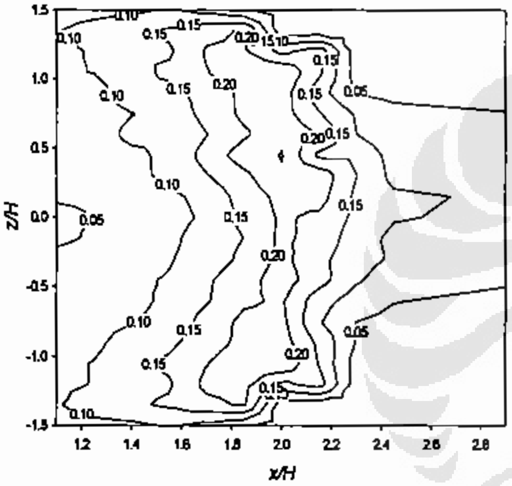
(b) $y/H = 0.3$

Figure 6.
Contours of Mean Luminance Intensity with injection at l/H=4; I= 0.3
(contour interval 0.05)

Figure 7 (a) shows a nearly symmetrical pattern about the injection point. High fluctuation of gas concentration with RMS of luminance fluctuation more than 0.1 takes place within a region about ± H from injection point and height about 0.7 H. Outside the region the nitrogen concentration distribution does not fluctuate much as the RMS value reach a nearly constant low value below 0.06. A maximum value of RMS about 0.35 exists in the location about $y/H = 0.25$ above the injection exit. This location coincides with the position where the cross-stream gradient of mean luminance intensity ($\partial[L/Lo]/\partial[y/H]$) at Figs. 3(a) changes the trend of its value. In the shear layer region the concentration fluctuation is low due to effective mixing by strong turbulence which produce much uniform concentration of the injected gas. Furthermore, assessment on horizontal plane in Figs. 7(b) shows that the gas concentration fluctuation in the regions where the two symmetrically separated swirling structures are formed considerably are higher compared to the fluctuation in the other region.



(a) $z/H = 0$

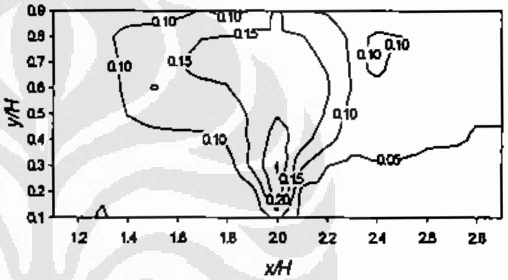


(b) $y/H = 0.3$

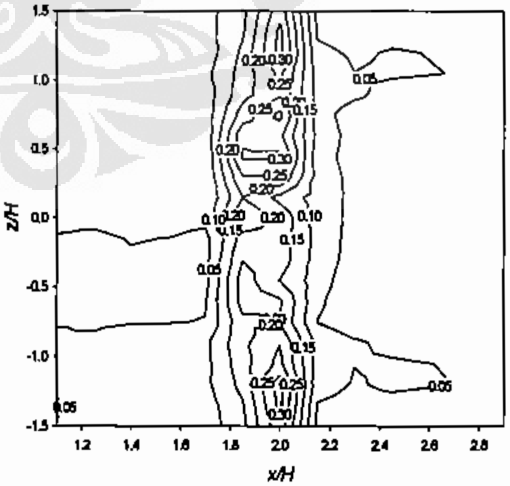
Figure7.
RMS of Luminance fluctuation with injection at l/H=2; I= 0.04 (contour interval 0.05)

In the case of $I = 0.3$, Figs. 8 shows that RMS of luminance intensity fluctuation more than 0.1 takes place within a narrower streamwise interval at lower region below $y/H = 0.5$ compared to the case of $I = 0.04$, and approximately the same width in the upper region. However, the maximum value of RMS of luminance intensity fluctuation is lower than that of the case $I = 0.04$, which indicates the gas concentration is less fluctuated when specific momentum injection is increased, and it is especially important at just above the injection point.

Figures 9 present the contours of RMS of luminance intensity fluctuation in case $l/H = 4$ for $I = 0.04$. The contour taken at vertical center in Fig. 9(a) shows that the region with high RMS value corresponds to the region where the injected gas is mostly distributed. A maximum RMS value about 0.36 is located near wall at a distance about 0.1 H from the injection point. Outside this region, the RMS of luminance intensity is still relatively high with value no less than 0.11. Furthermore, the RMS contour at horizontal plane in Figs. 9 (b) show that high fluctuation of injected gas concentration also occurs in the entire places of assessment. These observations suggest that in this case, a turbulence controlled mixing process take place in a rapid, intense manner and highly fluctuated fashion all at once.



(a) $z/H = 0$

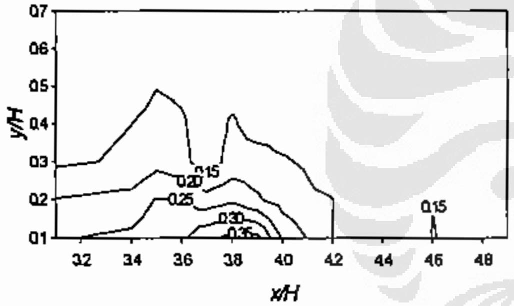


(b) $y/H = 0.3$

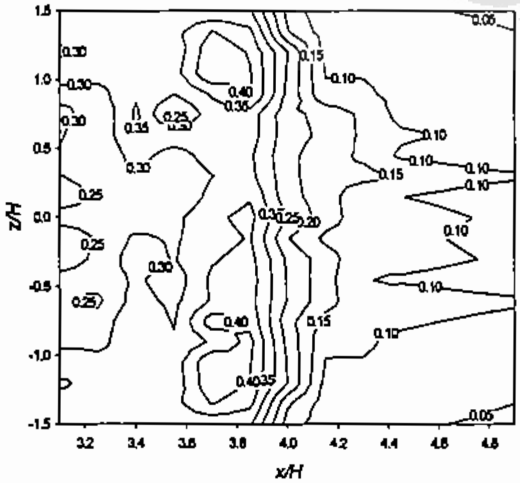
Figure 8.
RMS of Luminance fluctuation with injection at l/H=2; I= 0.3 (contour interval 0.05)

Meanwhile, for the case of $I = 0.3$ Figs. 10(a) shows a rather symmetrical contour about the injection. The region with high

RMS value is located directly above the injection point up to shear layer that again confirms the deep penetration of the injected gas through the shear layer. The maximum value of RMS is about 0.26, which is lower than that in case $I = 0.04$ for the same location of injection point. The fluctuation level of luminance intensity in the down stream of this region is significantly different to that in the location upstream of it. The amount of injected gas that reentrains to the recirculating flow formed down stream of the injection point fluctuates more than that which distributes toward the recirculating flow upstream of the injection point. Further, the RMS of luminance fluctuation contours at horizontal plane in Fig. 10(b) indicates that the gas concentration fluctuation is almost similar for every stream wise location along spanwise direction.

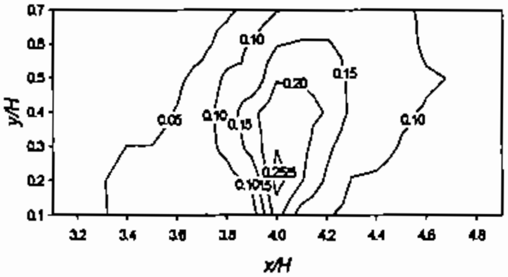


(a) $z/H = 0$

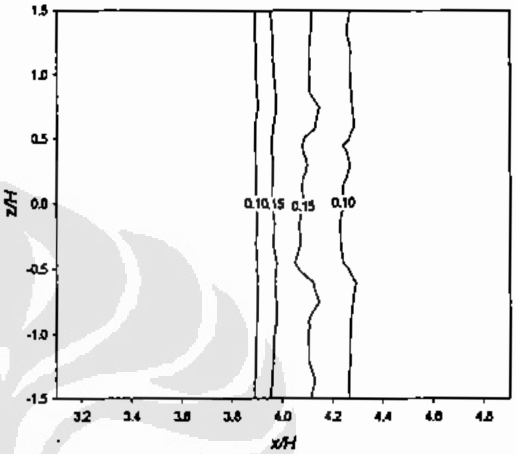


(b) $y/H = 0.3$

Figure 9.
RMS of Luminance fluctuation with injection at l/H=4; I= 0.04 (contour interval 0.05)



(a) $z/H = 0$



(b) $y/H = 0.3$

Figure 10.
RMS of Luminance fluctuation with injection at l/H=4; I= 0.3 (contour interval 0.05)

Another feature that can be revealed from the contours of RMS of luminance fluctuation is the effect of gas injection to the turbulence intensity in the recirculation zone. At both cases of injection locations, the maximum value of RMS of luminance fluctuation decreases as the specific momentum of injection is increased. This suggests indirectly that the turbulence intensity be suppressed as the momentum injection is increased, especially in the region near the base wall. This tendency agrees well with that reported by Yang et al.[5] from their velocity field data.

3.4. Spatial Correlation of Luminance Fluctuation

An importance aspect in elucidating the distribution characteristics of the injected gas is the spatial correlation of the gas concentration fluctuation represented as correlation between the fluctuation of luminance intensity. The spatial correlation is obtained by observing simultaneously (zero time delay) the luminance fluctuation at two points in the flow field. Then the correlation coefficient, R is calculated as:

$$R = \frac{\overline{L'_1 L'_2}}{\sqrt{\overline{L'^2_1}}\sqrt{\overline{L'^2_2}}} \qquad (1)$$

where L'_1 and L'_2 are luminance intensity fluctuations at point 1 and 2 respectively.

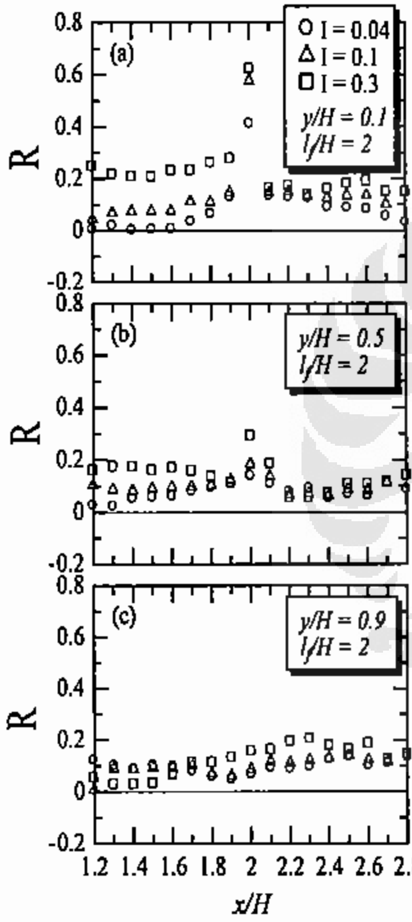


Figure 11.
Spatial Correlation of Luminance Fluctuation in case of of $l/H = 2$

Spatial correlation coefficients between fluctuation at injection location and at other location in the flow field are presented in Figs. 11 and 12, for three case of I. In the case of $l/H = 2$, Figs. 11 (a-c) show that within the recirculation zone ($y/H = 0.1$ and 0.5) the correlation curves of $I = 0.04$ and 0.1 are quite symmetrical about the injection location ($x/H = 2$) with peak values located above the injection point. For $I = 0.3$, the correlation curve shows that upstream from the peak, the correlation coefficient is higher than that in the downstream. The effect of increasing the specific momentum ratio to the increase of correlation coefficient is remarkably seen. This tendency is more notable at upstream location, compared to that at down stream from injection point. On the other hand, at the shear layer region ($y/H = 0.9$) the correlation coefficient curves are quite flat with no clear peaks and the coefficients remain at low values. However, in case of $I = 0.3$ the correlation is stronger in the downstream region of injection position. This result suggest that more amount of the injected gas reaches the shear layer and the gas is brought to the down stream by the shear flow.

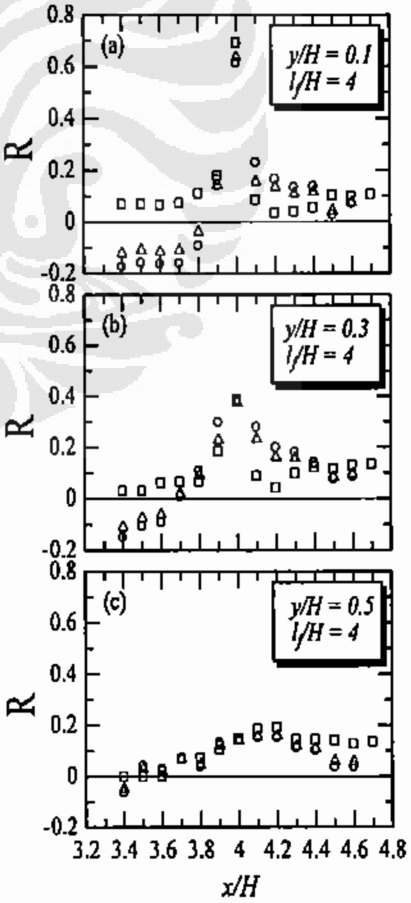


Figure 12.
Spatial Correlation of Luminance Fluctuation in case of of $l/H = 4$

Meanwhile in the case of $l/H = 4$ Figs. 12(a-c) shows that near the base wall, at $y/H = 0.1$ and 0.3, the correlation coefficients for $I = 0.04$ and 0.1 have negative values at upstream position from injection point. In this case, reverse flow with higher velocity forces the most fraction of injected gas just entering the flow field toward upstream direction, whilst the remaining fraction which is still in the vicinity of injection point rapidly mixes with the air flow due to strong turbulence. As a result, a concentration increase in the upstream of injection point and a concentration decrease in the injection point occur simultaneously. However this negative correlation does not occur at $y/H = 0.5$ and the coefficients are positive for all case of specific momentum injection. Moreover at the downstream of the injection point as the ratio of specific momentum injection is increased, the correlation coefficient decreases at $y/H = 0.1$ and 0.3, and increase at $y/H = 0.5$. These results indicate that when injected with higher ratio of specific momentum the amount of gas which distributes in the recirculation zone decreases,
whilst the amount of the gas which distributes in the shear layer region increase.

4. Conclusion

A laser-sheet based visualization utilizing the Mie scattering and the quantification of the luminance intensity from the scattered light has been successfully used to evaluate the mixing of non-reactive nitrogen gas injected behind a backward facing step flow. The discussion focussed on the effect of the specific momentum ratio and the location of the injection to the development of injected gas jet and the mixing. The main results can be summarized as follows:

1. Regarding the gas concentration distribution, in the case of injection with low specific momentum, the gas distributes within a narrow region around the injection point without deep penetration. As the momentum of injection is increased the recirculation region splits into two parts, and then the distribution of the injected gas exhibits different tendency which depends on the location of the injection point. In the case of near-step injection the gas distributes mainly toward upstream of injection point due to the effect of local reverse flows which supports convective mass-transfer toward this region. However, the fraction of gas, which distributes to the region reaches a certain maximum denotes by the relative luminance intensity whose value was not remarkably changed around $L/L_o = 0.45 \sim 0.5$, as the momentum ratio of injection is further increased from 0.3 to 0.5. Meanwhile in case of injection near-reattachment point, as the jet penetrates through the shear layer region the gas distributes mainly toward downstream of injection point due to the effect of the free stream and then re-entrains into the down stream recirculation zone. Furthermore, mixing is more rapid, intense and better which is controlled by the high shear-turbulence in the region.
2. As the specific momentum of injection is increased, the maximum fluctuation level of the gas concentration decreases. A reduction up to 30 % of the maximum RMS value of luminance intensity fluctuation can be observed when increasing specific momentum ratio of injection from 0.04 to 0.3. This suppression of fluctuation level reveals the reduction of turbulence intensity in the recirculation region, especially in the region near the base wall.
3. Spatial correlations suggested that mixing between injected gas and surrounding air was more rapid and better in case injection in the near reattachment point due to higher turbulence in the region.

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