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Temperature Measurement of Dilute Hydrogen Flame by Digital Laser-Speckle Technique

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Abstract: In this paper, temperature measurement of axisymmetric dilute hydrogen flame is described using digital laser-speckle technique, which allows the measurement of refractive index field of the flame without any tracers. The measurement system consists of laser and CCD camera, which are placed in-line configuration. The temperature field of the flame is derived from the refractive index field using the cross-correlation analysis of the speckle pattern with and without flame. The influence of the species concentration on the temperature measurement is evaluated from the gas composition in the flame using gas chromatography. It is found that the temperature field measured by the present method with concentration correction agrees with that of the thermocouple measurement within an experimental accuracy, suggesting the usefulness of this measurement technique.

Keywords: Temperature, Optical measurement, Visualization, Laser speckle, Hydrogen flame

1. Introduction

The dilute hydrogen flame is an important topic of interest both from fundamental and practical point of view in combustion engineering. The influences of diluents on NOx formation of hydrogen flame has been studied by Feese and Turns (1998), Barlow et al. (1999), Rortveit et al. (2002), because they are useful for the design of combustor having flue-gas recirculation system. It is generally known that the hydrogen flame becomes more inactive to the chemical reactions at higher fraction of diluents, which is due to the reduction in the calorific value of the fuel and the reduced buoyancy of the flame (Chinone and Fujisawa 2004).

Temperature field of combusting flame is an important topic of interests for understanding the physical and chemical phenomena in the flame (Shalaby et al. 2007). In the measurement, optical technique plays an important role, because it can measure the temperature field without disturbing the flame, which is in contrast to the intrusive measurement by thermocouples and so on. The optical techniques considered previously for the flame temperature measurements are laser-speckle photography (Shakher et al. 1994; Walsh and Kihm 1995), interferometry (Zhang and Ruff 1994; Tieng, et al. 1996) and rainbow schlieren deflectometry (Albers and Agrawal 1999; Wong and Agrawal 2006). Although these techniques allow quantitative measurement of temperature field in the combusting flame, the accuracy of measurement highly depends on the assumption that the local composition of the flame is the same as that of the air at the same temperature. Therefore, the effect of species concentration on the temperature measurement is examined by numerical simulation, and it is crucial in the optical measurement of flame temperature (Qin et al. 2002).

Recently, the digital laser-speckle technique is introduced into the measurement of density field of the helium jet using the cross-correlation analysis of the speckle displacement (Ko and

Okamoto, 2004), which provides high spatial-resolution in the measurement of density field in contrast to other optical techniques. Therefore, further study of this optical technique is useful for application to the flame temperature measurement.

The purpose of this paper is to study the temperature measurement by digital laser-speckle technique for application to dilute hydrogen flame. An attention is placed on the evaluation of correction factor in optical temperature measurement derived from the species concentration distribution in the flame.

2. Temperature Measurement by Digital Laser-Speckle Technique

Figure 1 shows a schematic illustration of the laser-speckle system for temperature measurement of axisymmetric flame. When the flame is illuminated by lasers, speckle pattern shifts normal to the temperature gradient of the flame due to the refractive-index variation with temperature. Such line of sight measurement of refractive index n can be represented by the following integral equation, when the flame is kept axisymmetric and the collimated laser-light is supplied to the test section (Walsh and Kihm 1995).

$$\frac{n(r)}{n_\infty} = 1 - \frac{1}{\pi}\int_r^\infty \frac{\alpha(y)}{\sqrt{y^2 - r^2}}\,dy \tag{1}$$

where r and y are coordinates as shown in Fig.1 and the angle of refraction α is expressed by the following equation.

$$\alpha(y) = tan^{-1}\frac{\Delta y}{L} \tag{2}$$

where Δy is the speckle displacement and L is the distance between the target flame and the imaging plane of camera.

The refractive index n of the flame can be related to the gas density ρ, which is a function of temperature, as follows:

$$n(r) = 1 + \rho K_{mix} \tag{3}$$

where K_{mix} $(= \sum Y_j K_j)$: Gradstone-Dale constant of the combustion gas, K_j : Gradstone-Dale constant of each composition gas, and Y_j : mass fraction of each composition gas. Thus, the refractive index of the flame is not only a function of temperature but also a function of species concentrations. On the other hand, the density ρ is related to the temperature T through the ideal gas law:

$$\rho = \frac{p}{R_0}\cdot\frac{W_{mix}}{T(r)} \tag{4}$$

where p: pressure, R_0: universal gas constant, W_{mix} $(= (\sum Y_j / W_j)^{-1})$: molecular weight of the combustion gas, W_j : molecular weight of each composition gas.

By substituting Eq. (3) into Eq.(4), the following equation is obtained after normalization.

$$T(r) = \frac{T_{air}(n_{air} - 1)}{n(r) - 1}\cdot\frac{K_{mix}W_{mix}}{K_{air}W_{air}} \tag{5}$$

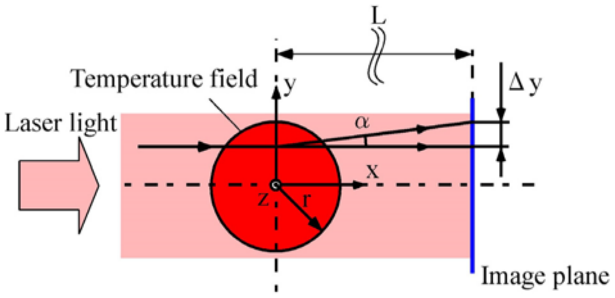


Fig.1 Principle of laser-speckle technique for axisymmetric flame

Note that $K_{mix}W_{mix} / K_{air}W_{air}$ is the correction factor of the combustion gas, which represents the influence of the molecular weight and Gradstone-Dale constant of the combustion gas, where subscripts $_{air}$ and $_{mix}$ indicate variables of air and combustion gas, respectively. The temperature $T(r)$ can be obtained from Eq.(5), when the refractive index $n(r)$ is determined from Eqs.(1) and (2) and the correction factor is evaluated from the composition measurement by gas chromatography.

3. Experimental Method

3.1 Flame Visualization

A schematic illustration of the experimental apparatus used in the present experiment is shown in Fig.2. The hydrogen gas is mixed with the helium gas in the mixing chamber, and the mixture gas is supplied to the test section through the straight vertical fuel tube having a vertical length of 300mm with an inner diameter of 6mm. Note that the fuel velocity is set to 0.3m/s in the present experiment. Thus, the fully developed laminar pipe flow is expected at the tube exit. The flow rate of each gas is measured by the volumetric flow meters located between the gas tanks and the mixing chamber. The volume fraction of hydrogen and helium is set to 6:4 in the present experiment. In order to avoid the flame flickering, a uniform co-flow of air is supplied to the test section through a honeycomb having an area of 120mmx120mm (Fujisawa and Nakashima 2007). Note that the surrounding co-flow velocity of air is 0.024m/s in the present experiment.

In order to confirm the axisymmetry of the whole dilute hydrogen flame, the flame visualization is carried out using the water spray containing NaCl, which is supplied to the surrounding air-flow using a ultrasonic humidifier. Such flame visualization technique is very effective to observe the reaction zone of the dilute hydrogen flame, which is invisible without visualization technique (Fujisawa et al. 2007, 2008). The visualized flame was taken by a color CCD camera having a spatial resolution 769x492pixels with 8 bits for each RGB.

Figure 3 shows the visualized color image of the reaction zone in dilute hydrogen flame issued from the fuel tube. The dilute hydrogen flame is clearly observed by the orange color using the flame reaction of Na. The intense orange area corresponds to the reaction zone, which is formed along the shear layers on both sides of the fuel tube and they gather at the tip of the flame. The dark area near the tube exit indicates lower temperature area, where the reaction is inactive. Such observation of dilute hydrogen flame indicates that the flame is steady and axisymmetric in shape. The confirmation of flame axisymmetry is very important in the present study, because the present temperature measurement algorithm assumes that the flame is axisymmetic with respect to the flame axis.

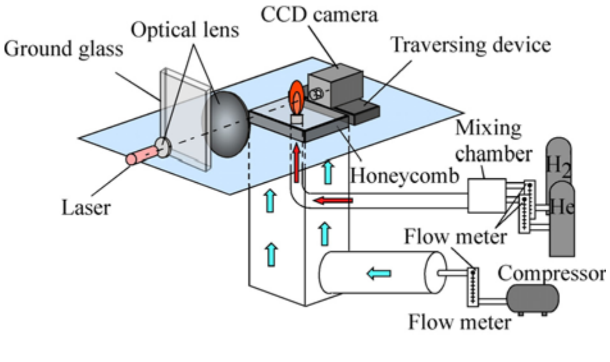


Fig.2 Schematic illustration of experimental system

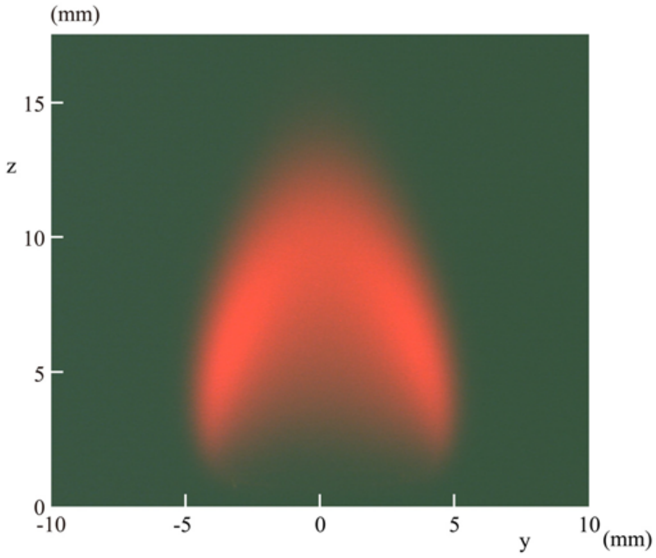


Fig.3 Visualization of dilute hydrogen flame

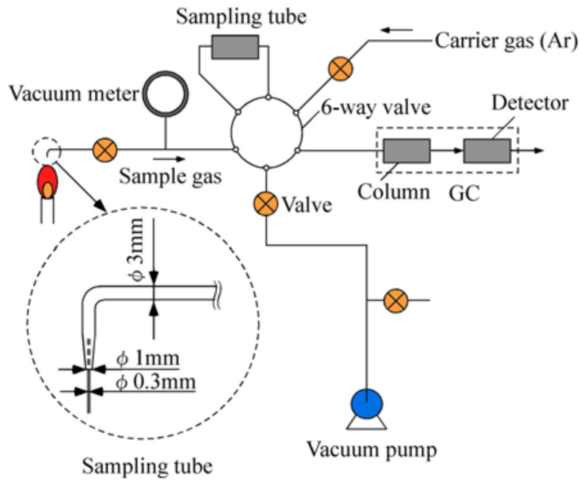


Fig.4 Gas chromatography and sampling probe for species concentration measurement

3.2 Species Concentration Measurement

The species concentration distribution of the combustion gas in the dilute hydrogen flame is measured by gas chromatography (GC) using the sampling probe. The schematic illustration of the measurement system is shown in Fig.4. The GC can analyze the composition gas of the dilute hydrogen flame, such as H_2, He, N_2, O_2 and H_2O. The sampling probe used in the present measurement is shown in Fig.4, which samples the combustion gas in the flame. It should be mentioned that the sampling probe is made of quartz having a tapered tube with an inside diameter of 0.3mm at the inlet, which increases gradually to 1mm along the probe axis. The outer diameter of the probe is 1mm at the inlet and it increases gradually to 3mm along the probe axis. Such configuration of the sampling probe is designed to minimize the disturbance against the target flame (Tieng et al. 1996).

During the sampling process, the combustion gas is sucked by the vacuum pump, and the sampled gas goes to the column in the GC for the composition analysis. The suction velocity at the inlet of the probe is controlled by a valve. The combustion gas is kept in the sampling tube, and is conveyed to the column of GC using Ar as a carrier gas. The sampled gas is analyzed in the GC using the thermal conductivity detector, which allows the measurement of five species concentration in the flame. Those measured in this study are H_2, He, N_2, O_2 and H_2O. In this study, the species concentration of H_2, He, N_2, O_2 are directly obtained from the gas analysis, while that of H_2O is obtained from the chemical reaction of hydrogen and oxygen, that is $2H_2+O_2 \rightarrow 2H_2O$.

3.3 Temperature Measurement by Digital Laser-Speckle Technique

The line of sight measurement of temperature field of the dilute hydrogen flame is carried out using the in-line illumination of laser having wavelength 635nm. The laser beam is expanded by two convex lenses, which allow the collimated light at the test section. By introducing the ground glass between the two optical lenses, speckle pattern is created on the imaging plane of the CCD camera (see Fig.2). The spatial resolution of the CCD camera is 1008x1018 pixels with 8bits in gray level. The imaging area of CCD is 9.072mmx9.162mm. It should be mentioned that the CCD camera is placed on the traversing device to measure the whole target area of the flame, which corresponds to 20mm in height and 36mm in width. The maximum pixel displacement was about 8 pixels in the present measurement. An example of speckle pattern is shown in Fig.5, which is taken near the exit of the fuel tube. Note that the full image size is 1008x1018pixels and the enlarged view of the speckle pattern (50x50pixels) is shown in the lower right hand corner of the image. The speckle pattern consists of dots of 2-3 pixels, which meets the requirement of high accuracy in the cross-correlation analysis of the speckle displacement. The dot size of the speckle pattern can be controlled by the change of roughness on the ground glass.

The speckle image on the CCD plane with and without flame is analyzed by cross-correlation algorithm combined with the sub-pixel analysis (Kiuchi et al. 2002). The interrogation window size used in the present measurement is 21x91 pixels, which is elongated in horizontal direction. An

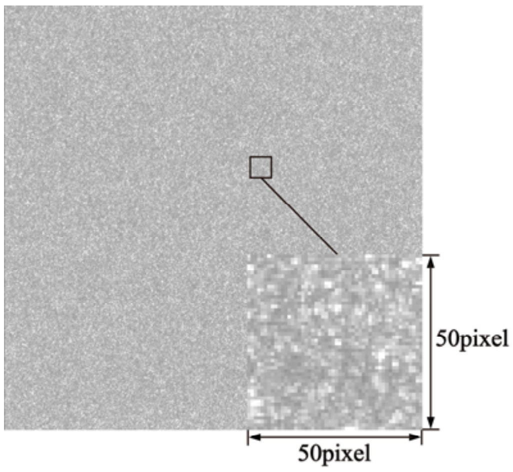


Fig.5 Laser speckle pattern

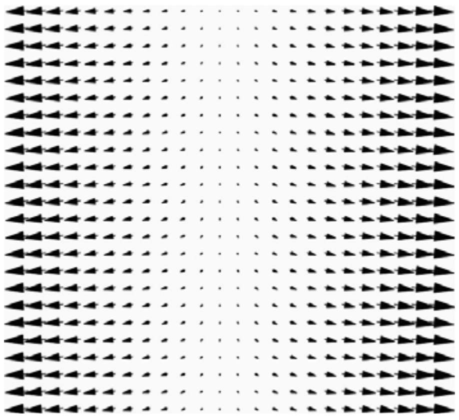


Fig.6 Speckle displacement map

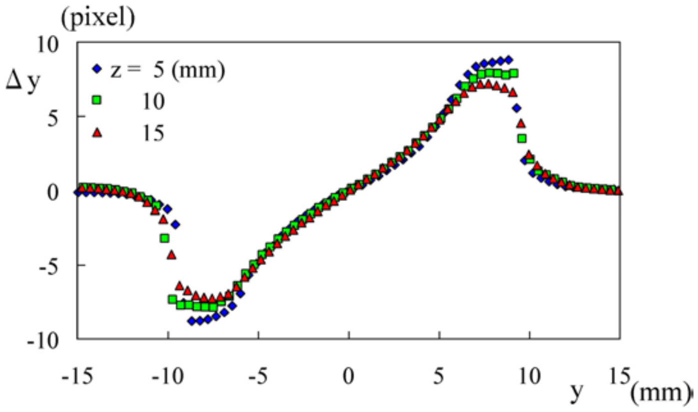


Fig.7 Distribution of speckle displacement

example of speckle displacement obtained from the analysis is shown in Fig.6. It is found that the speckle pattern displaces almost in horizontal direction, which shows that the temperature gradient is found mainly in the horizontal direction. The typical distributions of speckle displacement in the horizontal planes at 5mm, 10mm and 15mm from the tube exit are shown in Fig.7, which covers the whole measurement area of 30mm in horizontal direction. These results indicate that the speckle displacement is largest in magnitude in the outer region of the flame and they are symmetric with respect to the flame center, regardless the vertical positions of the flame. These speckle displacements cross the zero displacement at the tube axis. It should be mentioned that the speckle displacements are almost zero on both sides of the distributions, which indicates negligible temperature gradient in the outer edge of the measurement area.

4. Results and Discussion

4.1 Species Concentration Contour

Figure 8 shows the species concentration contours of the dilute hydrogen flame, which are measured by GC using the sampling probe. Each contour map shows iso-concentration contour of H_2, He, N_2, O_2 and H_2O. It is clearly seen that the concentration of H_2 is higher near the fuel tube exit and it decreases suddenly with an increase in the distance from the tube exit in horizontal and vertical direction, while the fraction of He decreases gradually with the distance from the tube exit. The N_2 contour shows small value near the tube exit, but it approaches to a volume fraction of N_2 in the surroundings as the distance from the tube exit increases. On the other hand, O_2 contour shows a small value in the reaction zone, and it increases gradually to the volume fraction of O_2 in the surroundings. The contour of H_2O indicates a small fraction near the tube exit but it becomes higher in the flame, because H_2O is generated by the reaction of H_2 and O_2. It should be mentioned that the

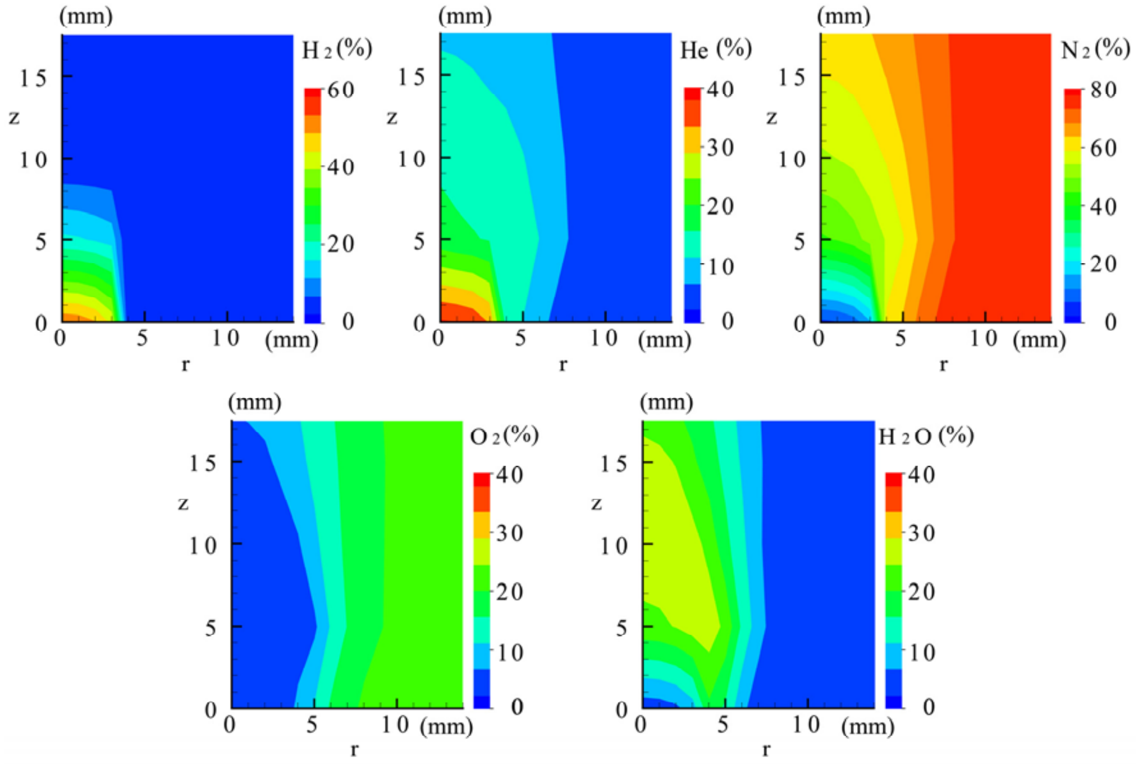
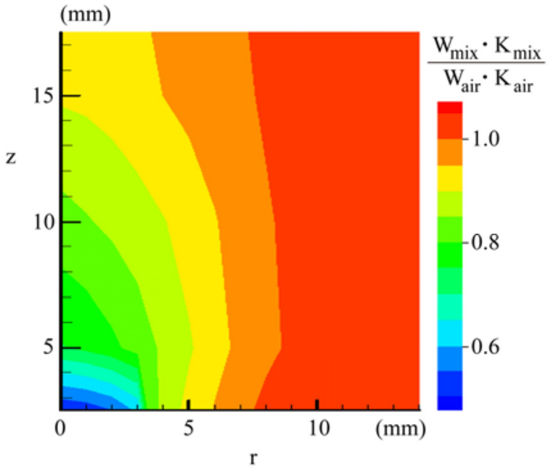


Fig.8 Concentration contour



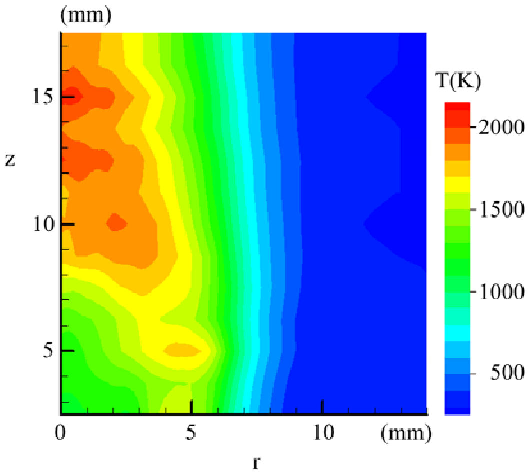


Fig.9 Correction factor map

Fig.10 Temperature contour

fraction of H_2O is smaller near the tube exit, which shows inactive chemical reactions in this region. These species concentrations are used for evaluating the correction factor $K_{mix}W_{mix} / K_{air}W_{air}$ in Eq.(5) for the temperature measurement, which is displayed in Fig.9. It is found that the lower correction factor is observed near the tube exit and it increases gradually as the distance from the tube exit increases. In the far region, the correction factor reaches 1, which corresponds to negligible influence of species concentration on temperature measurement. It should be mentioned that the smaller value of correction factor in the flame is mainly due to the presence of H_2 and He in the flame. These gases have smaller molecular weight than that of the air, so that the ratio of molecular weight W_{mix}/W_{air} becomes smaller in the flame.

4.2 Temperature Distribution

Figure 10 indicates the temperature contour of the dilute hydrogen flame, which is obtained from the digital laser-speckle technique in combination with the species concentration measurements. The temperature contour shows higher temperatures in the higher z position along the flame axis, while the temperature is lower near the exit of the fuel tube.

In order to confirm the accuracy of temperature measurement by digital laser-speckle technique, the thermocouple measurement is carried out in the dilute hydrogen flame. Figure 11(a),(b) shows the temperature distributions at z=5mm and 10mm, respectively. The results with and without concentration correction are shown in each figure, and they are compared with temperatures measured by Chromel-Alumel thermocouple having outer diameter of 0.3mm coated by Inconel, which minimizes the catalytic reaction on the wire surface. The influence of thermal conduction and radiation on the thermocouple measurement is corrected by the method proposed by Sislian et al. (1988). The accuracy of thermocouple measurement is estimated as 7.9%, which covers the influence of thermal conduction, radiation and the repeatability of flow-rate setting in the experiment. On the other hand, the accuracy of temperature measurement by laser-speckle technique in combination with concentration correction is estimated as 4.6% in 95% confidence level, which is due to the sub-pixel inaccuracy in the cross-correlation analysis, the numerical integration error in refractive-index measurement, the minor geometrical error in optics and the measurement error in concentration by GC. Therefore, the temperature distributions measured by the digital laser-speckle technique with concentration correction agree with those by the thermocouple measurement within an experimental uncertainty. It is expected that some deviations of temperature measurement in the outer region at z=10mm (Fig.11(b)) may be caused by the partial deterioration of axisymmetry of the flame. Such asymmetry of the flame has been observed by the presence of minor roughness at the fuel tube exit (Fujisawa and Nakashima 2007). It should be mentioned that the temperature distributions without concentration correction shows higher temperatures than those with correction, which is mainly contributed by the presence of H_2 and He in the dilute hydrogen flame.

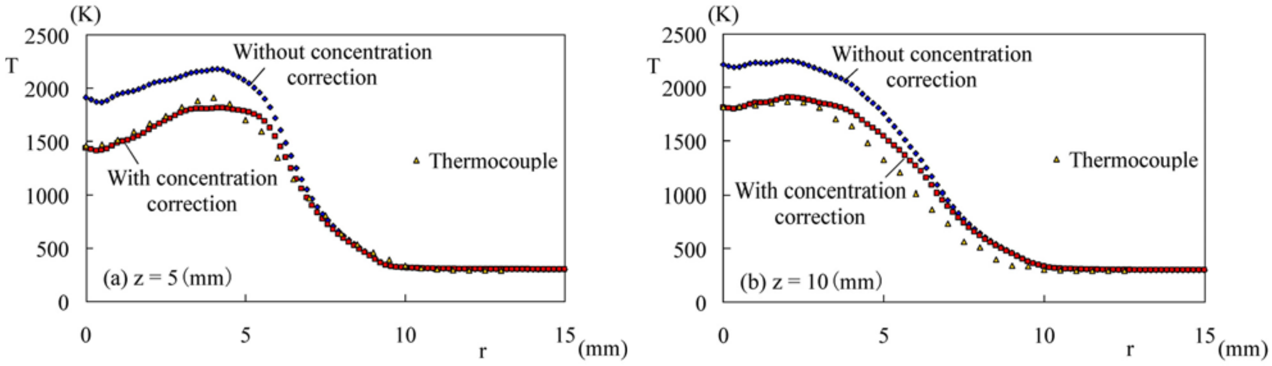


Fig.11 Comparison of temperature distributions

5. Conclusions

The temperature measurement of dilute hydrogen flame in axisymmetric configuration is carried out using digital laser-speckle technique in combination with the concentration measurement by gas chromatography. The measurement system consists of laser and CCD camera, which are placed in-line configuration. The axisymmetry of the flame is confirmed by the flame visualization technique using the flame reaction of water spray containing Na. The temperature field is evaluated from the speckle displacement obtained from the cross-correlation analysis with species concentration correction. The measured temperature field agrees with that of the thermocouple measurement within an experimental uncertainty. This result indicates that the digital laser-speckle technique is useful for temperature measurement of dilute hydrogen flame by evaluating experimentally the influence of species concentration distributions.

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