Effection of Gas Flow to Laser-Beam Measure

Z Li, Z L Ding and F Yuan
Department of Automatic Testing and Control, Harbin Institute of Technology, Harbin 150001, China

E-mail: lizhe1978@hit.edu.cn

Abstract. When laser-beam passes through non-isothermal and non-isoconcentration gas, measurement result is influenced by different refractive index in gas flow layer. This paper analyses the regularities of index of refraction distribution in gas flow field, presents the factors that effect on the measurement errors, estimates the position errors of the indicating light-spot and modifies the measurement result in laser-beam measure.

1. Introduction
In laser beam measurement, it often uses the measuring method that captures the indicative facular points from the generating laser by high rate digital camera. But gas mediator is interfered because of the long beam path and the breaking-out measured object; this influences the accuracy of the final measurement result [1]. According to gas dynamics of jet stream, this paper analyses the measurement errors regularities of breaking-outing measured object, it make sense to appraise and compensate the measurement accuracy of system.

2. The temperature and pressure mathematical model
The condition in this experiment can be regarded as a kind of non-isothermal and non-isoconcentration gas flow, whose temperature and density is much more different to surrounding mediator. So we must know the regularities of temperature field and density field of gas flow to get the refractive index of surrounding gas. When laser beam passes through the flame of measured object, it can test not only the interference of gas flow but the influence to the light intensity.

Figure 1. The gas flow structure.
As is shown in figure 1, after gas has ejected from ejector nozzle as speed \( u_0 \), the media of flow exchanges mass, momentum and heat with the surrounding media, gas mass flow and cross-sectional area increases along \( x \) axis continuously, then it makes a cone flow field of non-isothermal and non-isoconcentration in figure. Because of infiltrating of surrounding mediators, it makes the homogeneous-speed field triangle, like \( AO'D \) in figure. The section that \( O' \) is in is the transition section, the initial segment is from nozzle to this section, the main segment is after this section, \( ABC \) and \( DEF \) is outside boundaries. Above all are gas flow field. This paper mainly discusses the state that laser beam passes through the initial segment which influences beam obviously.

To non-isothermal and non-isoconcentration gas flow, because heat diffusion and substance diffusion is a little faster than momentum diffusion with surrounding mediator, the speed boundary is appreciably different from the temperature field and the density field in fact. But in engineering calculations, their boundaries can be regarded as the same, so we can only calculate one of variables in them to get the relation of the others. In the following text, we analyze the characteristic parameters of gas flow field.

(1) The field outside boundary equation

According to theoretical calculations and experiments, the flow inside and outside boundaries can be treated as straight-lines. From figure 1, \( BO' \) is the border layer circular cross-section radius \( R \) in the transition section and it is direct radio with \( x \) that is from \( O \),

\[
R = Kx = 3.4a
\]

In equation, \( a \) is turbulivity that shows gas fluid texture characteristic coefficient and its numeric value is defined by experiments; \( K \) is the outside boundary grade rate and it usually uses \( K=3.4a \) in axial symmetry flow.

From Figure 1,

\[
\alpha = \arctg(Kx/x) = \arctg(3.4a)
\]

\[
\frac{R}{r_0} = \frac{h_0 + s}{h_0} = 1 + \frac{s}{r_0 \tan \alpha} = 1 + 3.4 \frac{as}{r_0} = 3.4 \left( \frac{as}{r_0} + 0.294 \right)
\]

(2) The main segment temperature and density distribution.

According to the experiment conclusion, the self-modeling characteristics of gas flow field parameters have relations as follow,

\[
\frac{\Delta T}{\Delta T_m} = \frac{\Delta \rho}{\Delta \rho_m} = \sqrt{\frac{u}{u_m}} = \left[ 1 - \left( \frac{r}{R} \right)^{1.5} \right]
\]

If \( r/R = n \), then \( \frac{u}{u_m} = \left[ 1 - \left( \frac{r}{R} \right)^{1.5} \right]^2 \).

In this equation,

- \( r \) is the distance from random point in section to flow axis center,
- \( R \) is the flow radium in same section,
- \( u \) is the gas speed at point \( r \),
- \( u_m \) is flow axis line speed in same section.

Every point pressure in gas flow field is approximately equal to the pressure of surrounding mediator. In response to the equation of conservation of momentum, it gets,

\[
\pi r_0^2 u_0^2 = \int 2\pi r u^2 \, dr
\]

Both sides are divided by \( \pi R^2 u_m^2 \) and integrate,

\[
\left( \frac{r_0}{R} \right)^2 \left( \frac{u_0}{u_m} \right)^2 = 2 \int \left( \frac{u}{u_m} \right)^2 \frac{r}{R} \, d\left( \frac{r}{R} \right) = 2 \int \left[ (1 - \eta^{1.5})^2 \right] \eta \, d\eta = 0.0928
\]
According to the enthalpy equations of flow nozzle section and random section in main segment,

\[
\frac{u_m}{u_0} = \frac{0.96}{as/r_0 + 0.294}
\]  

(7)

The change of gas refractive index changes along with Kelvin temperature \( t \), gas pressure \( P \), wavelength \( \lambda \) [2,3],

\[
n_S = 1 + N(\lambda, P, t) \times 10^{-6} = 1 + 77.6 \frac{P}{t} \left( 1 + 7.52 \times 10^{-3} \lambda^{-2} \right) \times 10^{-6}
\]  

(11)

Integrating equation (9), (10), we can get the distribution graph of gas refractive index in flow field.

### 3. light beam curving calculation and examination

The change of gas refractive index changes along with Kelvin temperature \( t \), gas pressure \( P \), wavelength \( \lambda \) [2,3],

\[
n_S = 1 + N(\lambda, P, t) \times 10^{-6} = 1 + 77.6 \frac{P}{t} \left( 1 + 7.52 \times 10^{-3} \lambda^{-2} \right) \times 10^{-6}
\]  

(11)

While \( \lambda = 0.65\mu m \), \( P \) is approximate standard pressure, that is \( P = 101325 \text{Pa} \),

\[
n(t) = 1 + 0.800277 / (\Delta T + 273.15^\circ) \]  

(2)

Integrating the laser beam trace equation and the flow field outside boundary equation, we can calculate the space position coordinates where the beam enters the field.
so the light path occurs to be curving. In the same conditions, the bigger the temperature difference differs, the more obvious the curving is. Because the whole gas flow is axisymmetric and the position alteration of gas flow in flow field can be ignored for the whole light path, we can consider that the path is only angle change in field.

![Figure 3](image)

**Figure 3.** The light beam curving map in gas flow field.

Based on above equations,

\[ \sin \theta(x, y) = n_0 \sin \theta_0 / n(x, y) \]  \hspace{1cm} (12)

When beam enters, the entrance angle is angle between the flow outside boundary and the entrance beam, which is \( \theta_0 = \alpha \), \( n_0 \) is the refractive index out of the field.

In field,

\[ \theta' = \arcsin(\sin \theta_0 \cdot n_0 / n') \]

According to figure 3,

\[ \theta'' = 180' - 2\theta_0 - \theta' \]

The exit angle is \( \sin \theta = n' \sin \theta'' / n_0 = n' \sin (2\theta_0 + \theta') / n_0 \)  \hspace{1cm} (13)

When measured object is much further away from the laser beam screen, the light point deviation \( \delta h \) is,

\[ \delta h = l \cdot \tan \beta = l \cdot \sin(\theta - \alpha) \]  \hspace{1cm} (14)

![Figure 4](image)

**Figure 4.** Light point deviation in different nozzle temperature.

The measured object is 6 miles far away the screen, figure 4 shows that the light point deviation changes with the nozzle temperature.

For making sure the correctness of the result, acetylene flame whose central temperature can reach 3000°C, is being used as the test material to measure the position of He-Ne laser beam whose wavelength is 0.65μm on the screen wall six meter far away after passing through the flame.
Table 1. The theoretical deviation and the actual deviation of different distances between nozzle and laser beam.

| The distances between nozzle(3000℃) and laser beam | 20mm | 100mm | 250mm | 500mm | 1000mm |
|-----------------------------------------------------|------|-------|-------|-------|--------|
| theoretical deviation                               | 7.863mm | 6.095mm | 4.376mm | 3.109mm | 1.138mm |
| actual deviation                                     | 8.449mm | 6.514mm | 4.691mm | 3.343mm | 1.206mm |

The table shows the theoretical deviation and the actual deviation of different distances between nozzle and laser beam. We can find out that the deviation using the method of the calculation in this paper has approximately 8% errors compared with the actual deviation. These errors mostly come from the accuracy of measurement system and the random variation in experiment site.

4. Conclusion

According to above, it gets some conclusions,

- non-isothermal and non-isoconcentration gas flow causes the heterogeneous distribution of surrounding air refraction index and makes laser beam path curving, ultimately induces the measure image points offsetting the ideal position and generates measurement errors;
- The higher gas temperature in nozzle is, the more obvious the influence to light path and image point is;
- The further the path is away from flow nozzle, the less the influence is.

The theory in this paper has simplified the practical situation. In experiment site, air flow, heat absorb and release, aqueous vapor variation and other physical changes make air temperature distribution more complex, air refraction index and image points offset are much bigger and more random. This makes the measurement errors more than the theoretical values in this paper. But utilizing this theory, it can compensate part of errors in the calculation of processing image point center and reduce the influence of these measurement errors of the result.

References

[1] W.TylerEstler 1985 High-accuracy displacement interferon entry in air Applied optics 24 6.
[2] HUANG Zhan-hua CAI Huai-yu Li He-qiao and ZHANG Yi-mo Influence of Laser Beam Bending on Thickness Measurement of Hot Steel Plate Opto-Electronic Engineering 6 40–43.
[3] K.P.Birch and M.J.Downs 1993 An Updated Edlen Equation for there fractive index of air Metrologia 30 155–162.