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The influence of species composition on flow field's optical computerized tomography diagnosis

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ABSTRACT

The species composition is one of the factors which could affect the refractive index of flow fields. So, the determination of species composition should be a key point, when optical computerized tomography (OCT) methods are applied to measure the key parameters of flow fields. In this paper, the influence of species composition on flow field's temperature diagnosis will be discussed both in theory and experiment. The final results manifest that the determination of species composition could affect not only the specific temperature values, but also the structure and distribution of the temperature. Meanwhile, it is also found that the nonlinear regular of the maximal temperature variation with the distance between the cross section and nozzle is the same in different models. Finally, the condition, which could be applied to judge whether the effect of species composition can be omitted, is proposed.

1. Introduction

Along with the rapid development of modern aviation, aerospace, rockets and missiles, there is an urgent need to expand the full visualization and key parameters measurement technology from low to high temperature complex flow fields. Optical computerized tomography (OCT) technology, as a kind of real-time, stable and non-contact optical measurement method, has been widely used in the diagnosis of various flow fields [1–5]. Hence, it should have unique advantages in the visualization and key parameters measurement of high temperature complex flow fields.

However, the species composition, as a one of the factors which can affect the refractive index, should be initially determined before obtaining the temperature or electron number density distribution of the high temperature complex flow fields by OCT methods. Taking a flame flow field as an example, many researches have reported the determination of its species composition. For example, a number of articles regard that the species composition of the flames in the open system is air [6,7]. In addition, a lot of researches considered the real chemical reaction. However, they obviously ignored the existence of air absolutely [8,9]. Distinctly, for the flow fields in the open system, there is no doubt that the real measured flow field will be mixed with the air. Consequently, it needs to know the distribution of species composition for the measured flow field. In order to further improve the reliability, strengthen and expand the appliance of OCT techniques in the diagnosis of various flow fields, the effect of species composition should be discussed.

Aimed at this aim, this paper will revolve around the effect of the species composition of the flow field on the result of temperature reconstruction from both theory and experiment. The related research results are expected to provide valuable reference to better solve the visualization and key parameters measurement of flow fields by OCT methods.

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2. Theoretical analysis

A propane-air flame is chosen as a typical example for discussion.

2.1. Basic theory

For a compressible flow field with the average temperature is not too high, the dependence of the refractive index n on its temperature and pressure can be expressed as [10]:

$$n-1=\frac{1}{L}\left(A+\frac{B}{\lambda^2}\right)\frac{P}{\kappa T}, \tag{1}$$

where L indicates the Loschmidt number (2.687×10^{19} cm^{-3}), A and B are the constants related to the neutral particles of the flow field [11], λ is the probe wavelength, κ is the Boltzmann constant (1.38×10^{-23} J K^{-1}), P and T represent the pressure and the temperature of the flow field, respectively.

According to Eq. (1), to obtain the temperature distribution of the flame flow field from the experimentally measured refractive index, the pressure and the species composition (which decides the constants A and B) must be determined. So far, for the flame in the open system, the pressure is generally regarded as an atmospheric pressure (1 atm). For the species composition, two methods are usually adopted:

(1) The main component of the flame is the heated air (this article called model 1);
(2) The main components of the flame are the chemical reaction products by the complete combustion (called model 2 in this article).

2.2. The refractive index difference

Assuming that the flame flow field is composed of the heated air, the Eq. (1) should be expressed as:

$$\begin{aligned} n-1&=\frac{1}{L}\left(A_{air}+\frac{B_{air}}{\lambda^2}\right)\frac{P}{\kappa T}\\ &=\frac{1}{L}\left(28.71\times10^{-5}+\frac{1.6273\times10^{-14}}{\lambda^2}\right)\frac{P}{\kappa T}\quad(\lambda\text{: cm})\end{aligned} \tag{2}$$

If the model 2 is used, according to the chemical reaction equation of propane combust in air $C_3H_8+5(O_2+3.76N_2)=3CO_2+4H_2O+18.8N_2$, the ratio of CO_2, H_2O and N_2 in flame combustion flow field are 3/25.8,4/25.8 and 18.8/25.8. At this point, the constant A and B of the mixed flow field are represented as $A_{mix}=\frac{3}{25.8}A_{CO_2}+\frac{4}{25.8}A_{H_2O}+\frac{18}{25.8}A_{N_2}$ and $B_{mix}=\frac{3}{25.8}B_{CO_2}+\frac{4}{25.8}B_{H_2O}+\frac{18}{25.8}B_{N_2}$. Finally, Eq. (1) can be written as:

$$\begin{aligned} n-1&=\frac{1}{L}\left(A_{mix}+\frac{B_{mix}}{\lambda^2}\right)\frac{P}{\kappa T}\\ &=\frac{1}{L}\left(31.262\times10^{-5}+\frac{2.4688\times10^{-14}}{\lambda^2}\right)\frac{P}{\kappa T}\ (\lambda\text{: cm})\end{aligned} \tag{3}$$

In order to show the influence of species composition on the refractive index, Fig. 1 expresses the dependence of refractive index on the temperature under conditions of different species composition with the pressure of 1 atm.

As shown in Fig. 1, the refractive index difference caused by different species composition decreases with the increase of temperature. This means that the effect of species composition on the low temperature area will be more obvious in temperature reconstruction. In addition, in order to show the refractive index differences with different probe wavelengths, the results of 532 nm and 808 nm is given.

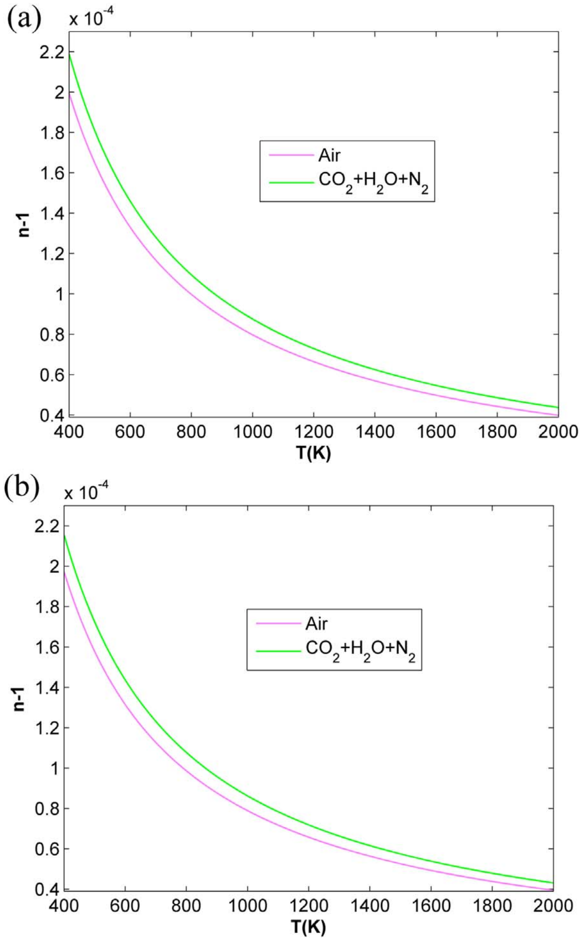

Fig. 1. The dependence of the refractive index on the temperature (a) 532 nm (b) 808 nm.

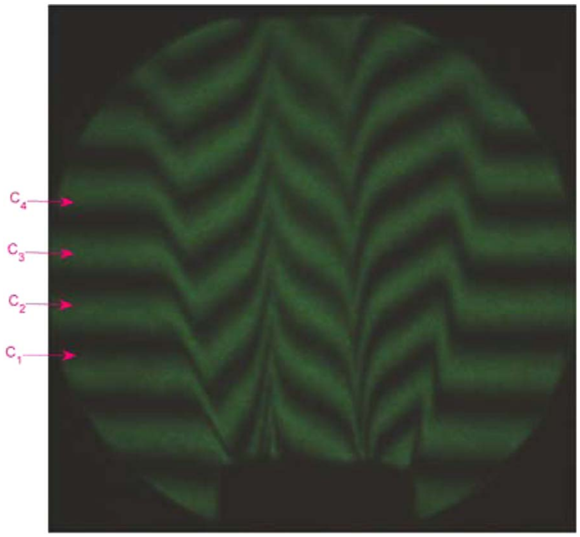

Fig. 2. Moiré fringes of the measured flame.

3. Experiment and results

The schematic diagram of experimental set up is the same as that of Ref. [12]. The experiment is achieved with the room temperature of 297 K, and the percentage purity of the propane gas is more than 95%.