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EXPERIMENTAL STUDY OF RADIATION HEAT TRANSFER COEFFICIENT OF DIFFUSION FLAMES

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Abstract. Basing on analysis of flame pictures given by visioscope by two-color method, the paper presents evolution of radiation heat transfer coefficient ε_s of soot in diffusion flames in air, in furnace and in combustion chamber of Diesel engine. ε_s reaches respectively its maximal value of 0.15; 0.30 and 0.45 in regions of maximal soot fraction of the three above flames.

1. INTRODUCTION

Calculation of radiation heat transfer from diffusion flames to combustion chamber is very complicated because it depends not only on geometric configuration of flame and combustion chamber but also on radiation heat transfer coefficient which is very difficult to determine in this kind of flame. The radiation heat transfer in diffusion flame is contributed by soot and gas components. In general, total radiation heat transfer coefficient of combustion products is given by the relation:

$$\varepsilon_T = \varepsilon_g + \varepsilon_s - \varepsilon_g \varepsilon_s,$$

where ε_T is total radiation heat transfer coefficient of combustion product, ε_g is radiation heat transfer coefficient of gas components and ε_s is radiation heat transfer coefficient of soot in combustion product.

In fact, in the combustion product of Diesel engine, soot is the main factor of radiation. It contributes up to 90% total radiation heat transfer from diffusion flame to wall of combustion chamber. In a lot of practical cases, one can consider that radiation of gas components in flame is about 10% of total radiation heat transfer. So in calculation of radiation heat transfer, we need determine only radiation heat transfer of soot.

The radiation coefficient of soot particulates cloud depends on its volume fraction in the medium. In recent years, some mathematical models have been established to predict this parameter. Some of them are simple, unidirectional that have been built to calculate average soot fraction such as [5], [6]. Others are more complicated that are integrated in CFD codes [2] such as KIVA III, FIRES, FLUENT... The last models give local value of soot fraction with higher accuracy [1], [3], [4]. These softwares, whether they are simple or complicated, are based on theories of fundamental soot formation, one of which is widely-used Tesner-Magnussen [7].

Once radiation coefficient is determined, the radiation heat transfer from diffusion flames can be calculated by some models such as direct radiation model, surface-to-surface radiation model (S2S), particular direction radiation model (DOM)... The experimental data is then important to test these numerical models.

In the present work, we focus the research on determination of radiation heat transfer coefficient of soot in diffusion flames by mean of experimental apparatus. Soot is carbon particles with very small size, distributes in flames under the form of solid particulate clouds. Radiation heat transfer coefficient of soot can be determined by the following expression:

$$\varepsilon_s = 1 - \exp(-KL),$$

with: $K = \dfrac{3.72 f_v C_o T}{C_2}$; C_2 =0.0143879 mK (constant); $C_o = \dfrac{36\pi nk}{(n^2 - k^2 + 2)^2 + 4n^2k^2}$

C_o depends on the real part n and the imaginary part k of dispersion index of soot. C_o ranges from 3 to 10. If the diameter of soot particles is too small, we can choose C_o=7 [1], thus K=1809.85f_vT.

Therefore, radiation heat transfer coefficient of soot can be determined finally:

$$\varepsilon_s = 1 - \exp(-1809.85 f_v T L).$$

According to this expression, radiation heat transfer coefficient of soot ε_s depends on volume fraction of soot f_v, temperature of flames at considered zone T and optical path length L. These parameters can be determined by different optical methods such as light scattering method, light diffusion method, two-color method... In this research, we determine these parameters by two-color method. The theoretical basis of this method is shown in [8].

2. EXPERIMENTAL APPARATUS

Fig. 1 introduces the schema of experimental apparatus. Three configurations of diffusion flames are studied: flame in the air, flame in industrial furnace and flame in combustion chamber of indirect injection Diesel engine Mazda. The most important equipment in the study is the visioscope AVL. The instrument is designed specially for study of combustion in internal combustion engine. In our present research, we have improved some auxiliary components of the videoscope for adopting the system to the two other cases [9].

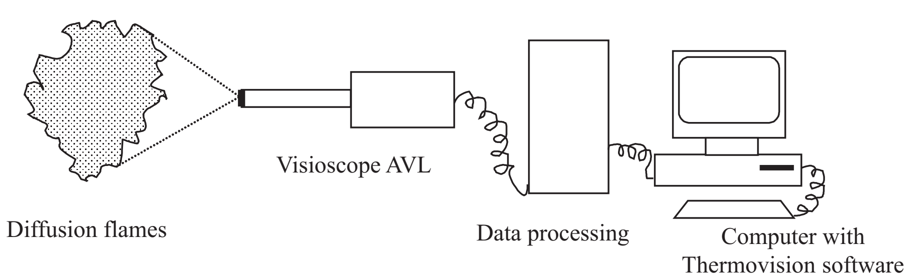

Fig. 1. Experimental set-up

The resolution of visioscope camera PixelFly CCD VGA color 24 bit is 640×480 pixels. Instantaneous flame pictures are recorded concurrently with radiant heat at two different wavelengths. The data are then sent to the computer for treating by the Thermovision software. The procedures are presented in [10].

With the current speed of taking photographs via visioscope, we can record real time pictures of flames. However, when we study relative values of flame at different crankshaft rotation angles in internal combustion engine, we have to shift a number of cycles so that the delay is approximating to the two successive picture-taking of the camera.

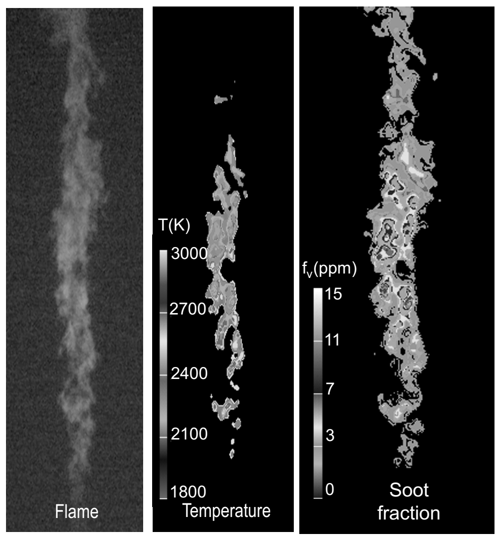

Fig. 2. Flame picture and result of analysis by two-color method

3. EXPERIMENTAL RESULTS

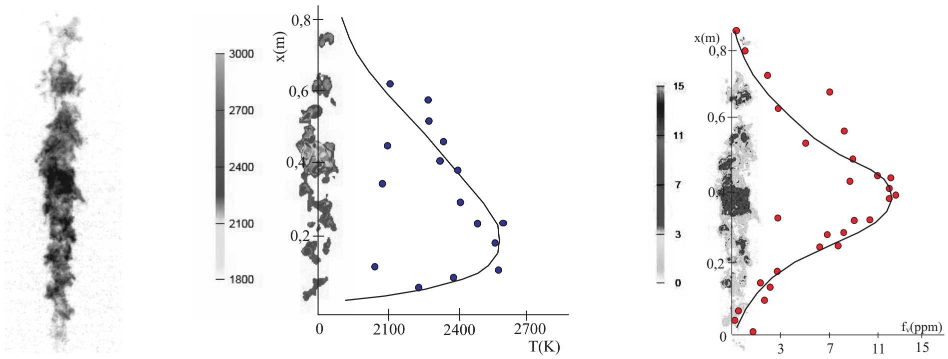

Fig. 3. Photographs of flames (a), temperature distribution (b) and soot fraction (c) according to flame axis X

Fig. 2 introduces the photograph of the flame, distribution of temperature and soot fraction in a typical measurement of the difussion flames in the air. Flame temperature and soot fraction are given by two-color method which was shown in [8]. Base on the result produced by Thermovision software, we can study the variation of temperature and soot fraction in different directions.

Fig. 3 introduces the variation of average temperature and soot fraction of the diffusion flame in open air. The average of temperature and soot fraction on a transversal cross-section of the flame is given by the following formula:

$$\overline{T} = \frac{\sum T_i L_i}{L} \quad \overline{f}_v = \frac{\sum \bar{f}_{v_i} L_i}{L},$$

T_i, f_{vi} temperature and soot concentration at zone i, L is optical path length of the flame at the considered cross-section.

These data are then used to determine radiation heat transfer coefficient of soot in the flames. Fig. 4 shows the variation of radiation heat transfer coefficient of soot ε_s versus flame height. The result shows that the variation of ε_s has the same tendency as the soot fraction one. The position $\varepsilon_{\max}$ is found between $T_{\max}$ and $f_{v\max}$. In case of our study (Diesel diffusion flame with injection pressure of 100bars, diameter of nozzle of 0.1 mm) the value ε_{max} is approximately 0.15.

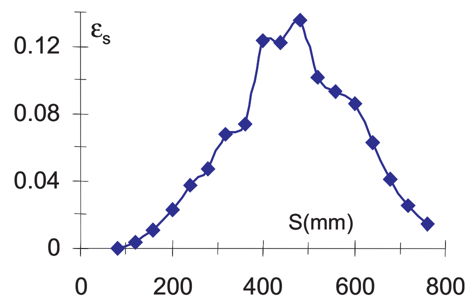

Fig. 4. Variation of radiation heat transfer coefficient according to flame height S (injection pressure of 100 bars)

Fig. 5 shows photographs of the flames, distribution of temperature and soot fraction in experimental furnace. The equivalent ratio ϕ of considered mixture is 0.9, 1.0 and 1.1. The result shows that soot fraction increases in function of equivalent ratio of the mixture [9]. The distance from the injection nozzle to the soot fraction maximal value position grows in function of equivalent ratio of mixture (Fig. 6). The maximum of radiation heat transfer coefficient of soot in furnace is approximately two times higher than that of diffusion flame in air (about 0.30).

Fig. 7 shows the result of flames in auxiliary combustion chamber of Mazda engine at 13^o, 18^o and 22^o crankshaft rotation angles. Close to TDC, combustion process relates to quantity of fuel introduced in delayed period, the mixture is well prepared so that only a little amount of soot are generated in spite of increasing of combustion temperature. At 18^o crankshaft rotation angle, diffusion combustion process is dominated and the amount of soot increases in zone of high temperature and abundant fuel.

After finishing injection, soot oxidation is occurred at high temperature zones so that soot fraction is reduced in combustion product.

Variation of temperature and soot fraction causes a direct influence on radiation heat transfer coefficient distribution (Fig. 8). At position of 18^o crankshaft rotate angle, the maximum of radiation heat transfer coefficient ε_s is 0.45, i.e. 1.5 times higher than its value at 13^o crankshaft rotate angle. The result shows that, in the first premixed combustion phase, the radiation heat transfer coefficient of Diesel flame in combustion chamber of engine is equivalent to its value in furnace. In the finishing stage of injection, combustion products distribute equally in combustion chamber, the curved line distributing radiation heat transfer coefficient is more smoothly, the average value of ε_s is 0.15, approximate to its value in case of diffusion flame in the air.

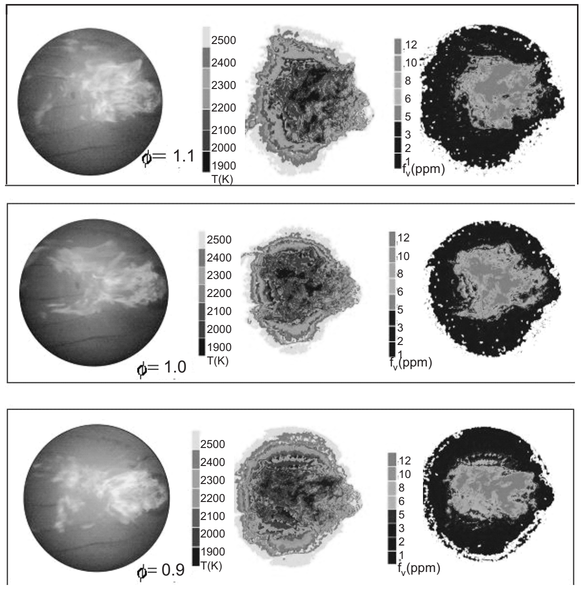

Fig. 5. Photographs of the flames and distribution of temperature and soot fraction in combustion chamber of furnace

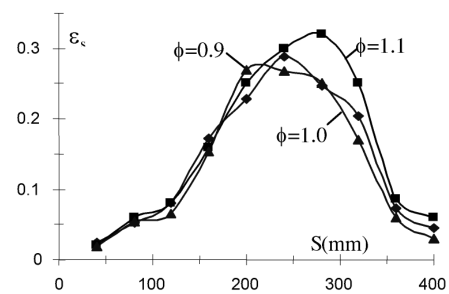

Fig. 6. Variation of ε_s according to the flame length S and ϕ

4. CONCLUSIONS

Radiation heat transfer coefficient ε_s depends essentially on soot volume fraction f_v in diffusion flames. The variation of ε_s and f_v versus flame height has the similar form. The position $\varepsilon_{\max}$ is found between $T_{\max}$ and f_{vmax}.

In industrial furnace, radiant heat coefficient of soot depends on equivalent ratio of mixture and its maximal value is about two times higher than that of flame in the air.

In the combustion chamber of Diesel engine, radiation heat transfer coefficient depends on the position of crankshaft. In the first combustion phase, the maximum radiation heat transfer coefficient of flames is equivalent its value in autoclave. In the final phase of combustion, this value reaches it value of diffusion flames in the air. $\varepsilon_{\max}$ in combustion chamber of Diesel engine is about three times higher than that of flame in the air

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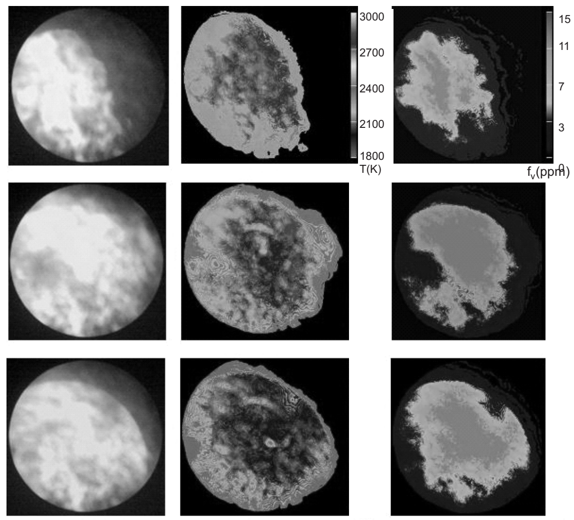

Fig. 7. Photographs of the flames (a), distribution of temperature (b) and soot fraction (c) in combustion chamber of Mazda engine (speed 1600 rpm, 60% load)

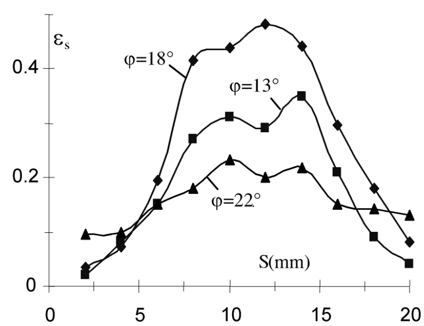

Fig. 8. Variation of radiation heat transfer coefficient according to the flame length S at different crankshaft angles in combustion chamber of Mazda engine

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NGHIÊN CỨU THỰC NGHIỆM HỆ SỐ BỨC XẠ NHIỆT CỦA NGỌN LỬA KHUẾCH TÁN

Trên cơ sở kết quả phân tích ảnh của ngọn lửa cho bởi visioscope bằng phương pháp hai bước sóng, bài báo giới thiệu biến thiên hệ số bức xạ nhiệt ε_s của bồ hóng của ngọn lửa khuếch tán cháy ngoài khí quyển, trong lò đốt công nghiệp và trong buồng cháy động cơ. ε_s đạt giá trị cực đại 0,15; 0,30; 0,45 ở khu vực có nồng độ bồ hóng lớn nhất theo thứ tự ứng với ba trường hợp ngọn lửa trên đây.