Investigation of the effect of soot on the characteristics of the methane flame in a gas engine

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Abstract. The desire to penetrate into the mechanism of phenomena occurring in the luminous flame of methane from a gas engine, to answer many unclear questions, to obtain any generalized results requires clarifying the effect of soot dispersion and its concentration on the radiation (optical) properties of the flame using theoretical research. At the same time, the complexity of sampling soot from a methane flame creates certain conditions for assumptions about the possibility of spreading the spectral characteristics of massive carbon to soot in a flame. The paper presents studies on a number of carbon formation phenomena, taking into account data on the dispersion and concentration of soot, which can serve as the basis for obtaining more or less universal patterns for luminous flames. The issues considered in the paper are analyzed using the provisions of modern theories, taking into account experimental work performed using some particular results of the theory of a cloudy medium.

1 Introduction

The widespread use of methane, which gives off a luminous flame during its combustion, has led to a large number of research works to find out whether a luminous flame is a "gray" body and in what form Kirchhoff's law applies to a flame [1-3]. Thus, studies of the dispersed phase suspended in the flame are known. When sampling a surface, they tried to find out whether the optical properties of soot in the layer and soot suspended in the flame were the same. In carrying out most of the work, scientists sought to find the dependence of the absorption coefficient, which is included in the Booger-Baer law, on the wavelength λ for various flame properties. This made it possible to apply the dependence $\varepsilon_\lambda = f(\lambda)$, the solution of which, together with the Planck or Wien equation, allowed us to get an idea of the amount of energy emitted by a particular flame $\varepsilon_\lambda = f(\lambda)$. Due to the imperfection of measuring technology at that time, the research carried out did not answer a number of important questions explaining the cause of certain phenomena occurring in the flame. Insufficiently accurate measurements did not allow us to make the necessary generalizations and identify patterns inherent not in individual, particular flames, but in all or a large group of luminous flames [4-6].

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2 Methodology

A great study in the knowledge of the physics of turbid media, which include a luminous flame, was the theory developed by the English physicist Mil. The widespread use of this theory required the availability of a sufficiently advanced computing technique. However, the application of the provisions of this theory to a luminous flame, carried out in a number of experimental and theoretical works, allowed us to establish a number of very important and fairly universal patterns. Today, and in earlier studies, it is difficult to overestimate the importance of Kirchhoff's law for the theory of thermal radiation. Therefore, the question of the applicability of Kirchhoff's law to glowing flames could not but attract the attention of scientists. Schmidt und Buchwaldt, having conducted studies at various wavelengths, showed that Kirchhoff's law in its spectral application is applicable to flames [7].

At the same time, the complexity of sampling soot from the flame created a condition for assumptions about the possibility of spreading the spectral characteristics of massive carbon to soot in the flame. One of the first to be proved was the fact that flame carbon, which is in a finely dispersed state, is very different from massive carbon in terms of absorption and radiation properties. Massive carbon has a spectrum close to that of a gray body, whereas carbon black is characterized by a difference in absorption capacity at different wavelengths. A number of scientists have noted the fact that the magnitude of the absorption capacity of a luminous flame naturally decreases with increasing wavelength. These studies were mainly carried out using soot taken from the flame. And, apparently, Angstrom [8] was the first to propose for soot to record the dependence of the absorption coefficient on the wavelength for the visible region of the spectrum in hyperbolic form $K_\lambda = K_o/\lambda^n$. The researchers found the coefficient n experimentally and accepted it as constant. The K_o constant included the effect of concentration, and in some cases concentration and thickness of the flame layer. Subsequently, many researchers followed a similar form of recording this dependence for the visible region of the spectrum, and the values of n and K_o fluctuated within very wide limits determined by the type of fuel, combustion conditions, and research methods. However, when using the data obtained in the study of deposited soot for the flame, it was necessary to prove the legality of such a transfer. In this regard, it is necessary to focus on one of the most significant works in this field. Studies were conducted on the amyl acetate flame of a Gefner lamp. In this work, the correspondence between the absorption of soot suspended in the flame and soot in the layer was experimentally shown. An important result of this work was also the confirmation of the suitability of Booger's law for a luminous flame. Subsequently, Schack [9] confirmed the correspondence between the dependence of the absorption coefficient on the wavelength for deposited soot and soot suspended in a flame. Direct scattering measurements carried out by Kurlbaum [10] and other scientists have shown that the scattering does not exceed 1% and can be ignored. This confirms the fact that flames containing fine soot particles have been studied, for which, as modern studies have shown, scattering is insignificant. With larger particles, the optical properties of the soot suspended in the flame and the soot in the layer might not coincide.

In further works by Pepperhoff and Bahr [11], the infrared part of some tribes was also studied, for which, by analogy with the visible region, the following expression was used:

$$K_\lambda = C\lambda^{-(n-m\ \lg\lambda)},$$

where C, n, m - experienced coefficients

3 Results and considerations

When conducting a flame study, the values of the experimental coefficients varied widely depending on the fuel, the combustion method and other specific conditions. Therefore, the results of such experimental work are suitable only for those specific conditions for which they were obtained, and cannot be generalized. It is impossible to draw any practical conclusions by analogy with the studied flames, since the research was carried out on laboratory flames [12-14].

Due to the lack of accurate data on the dispersion and concentration of soot, a number of phenomena cannot be explained on the basis of these studies, and they cannot serve as a basis for obtaining more or less universal patterns for luminous flames. Such questions can be dealt with only with the application of the provisions of the theory of turbid media, which was done both in purely theoretical works and in experimental works performed using some particular results of the theory of turbid media.

It should be noted that in some cases, the use of such a simple form of experimental data processing as the expression $K_\lambda=C\lambda^{-n}$, is useful at the present time if it is necessary to obtain dependencies for specific conditions. In this case, without resorting to complex calculations, useful data can be obtained if scattering is neglected and the equation is integrated:

$$E = \int_{\lambda=0}^{\lambda=\infty} a_\lambda E_{o\lambda} d_\lambda \ ,$$

where $a_\lambda = 1 - exp(-K_\lambda l)$; E - flame emission; a_λ - the emissivity (absorption) ability of the flame; $E_{o\lambda}$ - radiation of a completely black body according to Planck; l - flame thickness.

There are known studies where attention has been paid to the question of the relationship between the temperature of carbon black particles and the gas phase in the flame [15-18]. This question is important both for flame pyrometry and for explaining the strong effect of intermediate decomposition products on flame radiation. Noting this phenomenon, Rummel and Veh [19] explained it by the fact that hydrogen, released from the particle and burning at its surface, heats the particle to a high temperature, as a result of which the radiation of the flame increases sharply. As a result, it is necessary to establish whether there is a temperature difference between the particle and the gas phase at all and, if possible, what value it can reach.

This issue was considered in great detail in [9], in which it was shown by calculation for a particle of about 0.0003 mm in size that the difference between the temperature of the particle and the temperature of gases in the flame cannot exceed 1 degree. Along with this, Rossler and Behrens [20] admitted the possibility of exceeding the temperature of the soot above the temperature of the gas phase. It should be noted that without careful measurement of the soot dispersion, no conclusions can be drawn only from measuring the temperature of the particles, since without estimating the proportion of scattering in the attenuation of luminosity, a large error can be made in determining the temperature. In the same works, despite the lack of particle size determination, the dissipation of thermal energy was neglected.

Turbid media include those in which one substance, which is in a finely dispersed state, is suspended in another substance. A luminous flame in which the smallest carbon particles are suspended is one example of a cloudy medium. The theory of light propagation in a cloudy medium was developed by Mil, who carried out the general integration of Maxwell's equations for a spherical particle and extended the results to a collection of particles, provided that the action of all particles can be considered as the sum of the action of individual particles, i.e. the removal of particles from one another is so great that the ray emitted by a separate spherical particle is not it will affect the neighboring particle. It can be assumed that as long as the concentration of carbon particles is such that they are not able to fill 1 см^2 of the surface, being located tightly next to each other, placing them in 1 см^3 does not threaten to violate this condition [21].

As a result of the solution performed by Mil, expressions are obtained that allow us to determine the coefficients of attenuation $K_{\lambda W}$, absorption $K_{\lambda T}$ and scattering $K_{\lambda S}$, which have an area dimension and represent effective attenuation cross sections. It is clear that $K_{\lambda W} = K_{\lambda T} + K_{\lambda S}$.

Moving from effective attenuation cross sections to dimensionless attenuation coefficients related to the cross-sectional area of the particle:

$$k_{\lambda W} = \frac{4K_{\lambda W}}{\pi d^2},\ k_{\lambda T} = \frac{4K_{\lambda T}}{\pi d^2},\ k_{\lambda S} = \frac{4K_{\lambda S}}{\pi d^2},$$

and considering that the complex refractive index of the medium in which the dispersed phase is weighted is equal to one, you can write the following expressions to determine the attenuation coefficients:

$$k_{\lambda W} = -2\left(\frac{\lambda}{\pi d^2}\right) R_e \sum_1^{\infty} i\nu(\nu+1)(-1)^{\nu}\left(C_\nu - b_\nu\right),\ k_{\lambda T} = 2\left(\frac{\lambda}{\pi d^2}\right)\frac{\nu^2(\nu+1)^2}{2\nu+1}\left(|C_\nu|^2 + |b_\nu|^2\right),$$

that is, the expressions for determining the attenuation coefficients are infinite series of amplitudes of partial electric and magnetic oscillations, which are expressed in terms of tabulated Bessel and Gankel functions:

$$C_\nu = C_\nu\left(\frac{\pi d}{\lambda}; \frac{\pi d}{\lambda/m}; m\right),\ b_\nu = b_\nu\left(\frac{\pi d}{\lambda}; \frac{\pi d}{\lambda/m}; m\right)$$

and can be determined by the specified parameters $\frac{\pi d}{\lambda}$; $\frac{\pi d}{\lambda/m}$; m.

It follows from these expressions that the attenuation coefficients depend on the parameter $\rho = \frac{\pi d}{\lambda}$ and the complex refractive index

$$m = \sqrt{e - i\frac{2\sigma}{C}\lambda} = n - ix,$$

where e – dielectric constant; σ – electrical conductivity; n – refractive index; x – absorption rate.

In the case of $m \neq f(\lambda)$, the attenuation coefficients depend on the parameter ρ, however, it should be borne in mind that in the infrared region the complex refractive index depends on the wavelength. In principle, the dependence of m on temperature is also possible. The well-known work by Bloch [22] provides solutions for small ($\rho \ll 1$) and large particles ($\rho \gg 1$).

For small particles

$$k_{\lambda W} = 4\rho I_m \frac{1-m^2}{m^2+2},\ k_{\lambda T} = \frac{8}{3}\rho^4\left|\frac{m^2-1}{m^2+2}\right|^2.$$

Therefore, at $\rho \ll 1$, the scattering is very small and can be neglected. As a result, we can assume that $k_{\lambda W} = k_{\lambda S}$. If we consider that $m = f(\lambda)$, then you can get

$$k_{\lambda W} = \rho I_m \frac{24nx}{\left(n^2 - x^2 + 2\right) + 4n^2x^2}.$$

Or, given that $n = f(\lambda)$ и $x = f(\lambda)$

$$M_\lambda = \rho I_m \frac{24nx}{\left(n^2 - x^2 + 2\right)^2 + 4n^2x^2},$$

that

$$k_{\lambda W} = \rho M_\lambda,$$

that is, for $M_\lambda = const$ $k_{\lambda W}$ depends linearly on ρ, and for $\lambda = const$ is proportional to *d*.

In this case, there is no dependence of $a_{\lambda W}$ on *d* for the flame

$$a_{\lambda W} = 1 - e^{-k_{\lambda W} N \frac{\pi d^2}{4} l} = 1 - e^{-\rho M_{\lambda} N \frac{\pi d^2}{4} l} .$$

Considering the soot density constant, you can get

$$a_{\lambda W} = 1 - e^{-const\ G M_{\lambda} \frac{e}{\lambda}} ,$$

where G – concentration by weight.

The function M_{λ} can be defined by the formula of A G Bloch

$$M_{\lambda} = 1.36(1 - 0.1\lambda) .$$

For large particles, scattering cannot be neglected. The change in the attenuation coefficients is complex and at ρ>6 can be described by an approximate ratio established by K S Shivrin

$$k_{\lambda W} = 2\left(1 + \frac{0.4}{\rho}\right) .$$

For luminous flames formed as a result of the combustion of gaseous fuel in the engine, the most interesting is the area where $d \approx \lambda$.

4 Conclusion

As follows from the above, the coefficients of attenuation, absorption and scattering depend on the parameter ρ and the optical properties of carbon black particles in the form of their complex refractive index. Therefore, for the study and analysis of the luminous flame of a gas engine, taking into account the presented provisions, it is necessary to take into account the value of the complex refractive index. Luminous flame when using gaseous fuel (natural gas) in a gas engine occur both during diffusion combustion and when using various methods of preliminary reformation. The use of available data on the optical coefficient of soot volumes allowed us to obtain a number of very useful consequences and draw useful conclusions both on the nature of the general solution and on finding out the optimal parameters. It should be noted that all the material presented in this work refers to medium-diameter particles without taking into account the polydispersity of the dispersed phase, which, most likely, will have a certain effect on the radiation properties of the luminous flame of natural gas. In addition, all optical coefficients in this work are obtained under the condition that $m \neq f(T)$. This is not entirely strict, since there may be a dependence in the mid-infrared region $m = f(T)$. But due to the fact that in the visible and near infrared regions the possibility of the influence of the $m = f(T)$ dependence decreases, the presented conclusions can also be considered approximate because the refractive index of the gas phase of the flame in which soot particles are suspended may not be equal to 1.

References

1. S. Spano, M. Savarese, A. Parente, F. Contino, H. Jeanmart, Fuel **362**, 130772 (2024).
2. Sh.H. Zhu, Yu.J. Huo, Zh.X. Zhao, X.G. Wei, B. Liu, Acta Astronautica **215**, 593-606 (2024).
3. O. Kümük, International Journal of Energy Studies **9(2)**, 239-253 (2024).
4. H.E. Gülcan, Applied Thermal Engineering **243**, 122654 (2024).
5. P. Jena, J.V. Tirkey, Energy **289**, 130068 (2024).
6. F. Catapano, S. Di Iorio, A. Magno, P. Sementa, B.M. Vaglieco, Energies **17(5)**, 1026 (2024).

7. E. Buchwaldt, Annalen der Physik **33**, 928 (1910).
8. E. Angstrom, Annalen der Physik **36**, 715 (1889).
9. A. L. Schack, Techn. Physik **6**, 530 (1924).
10. F. Kurlbaum, Physik Zeitscr. **3** 332 (1902).
11. W. Pepperhoff, A. Bahr, Archiv Eisenhuttenwessen **9**, 10 (1952).
12. L. Terri, G. Grandi, V. Tihay-Feliselli, J. V. Lorenzetti, F. Morandini, P. A. Santoni, International Journal of Thermal Sciences **195**, 108664 (2024).
13. R. Cai, K. Luo, X. Tang, Ch. Zhao, A. Liu, J. Xing, J. Fan, Advanced Powder Technology **35(3)**, 104365 (2024).
14. S. Klukas, M. Giglmaier, M. Underberg, S.M. Schnurre, M.M. Prenting, T. Endres, H. Wiggers, Ch. Schulz, M. Sieber, S. Schimek, Ch. O. Paschereit, N.A. Adams, Applications in Energy and Combustion Science **18**, 100263 (2024).
15. O.P. Lopatin, IOP Conf. Series: Materials Science and Engineering **919**, 052033 (2020).
16. D. Dalkhsuren, K. Iwabuchi, T. Itoh, T. Narita, M.I. Piash, B. Nachin, G. Sukhbaatar, Bioenergy Research **16(3)**, 1629-1638 (2023).
17. Ch. Wang, C. Kemunto Mesa, S. Bimenyimana, N. Bogonko, G. Adwek, Y. Mo, G. Norense Osarumwense Asemota, Ch. Yuan, Ya. Chen, Ch. Li, E. Ntagwirumugara, A. Nduwamungu, Energy Engineering **119(3)**, 863-881 (2022).
18. B. Ren, T. Zhang, Z. Wu, J. Li, E. Gao, W. Wang, J. Zhu, Sh. Yao, Plasma Chemistry and Plasma Processing **44(5)**, 1905-1923 (2024).
19. K. Rummel, P. Veh, Archiv Eisenhuttenwessen **10**, 489-493 (1941).
20. F. Rossler, H. Behrens, Optik **21**, 110 (1943).
21. J. Chen, H. Zhao, W. Li, H. Liu, Gels **10(2)**, 89 (2024).
22. A.G. Bloch, Yu.A. Zhuravlev, L.N. Ryzhkov, *Heat exchange by radiation* (Moscow, Energoatomizdat, 1991).