Knowledge E
Engaging minds

Conference Paper

Adaptation of Radiative Properties of the End Products of Fuels Combustion within the Temperature Range of 1,000...2,000 K

E. V. Toropov[1], L. E. Lymbina[1], and Yu. G. Yaroshenko[2]

[1]South Ural State University (National Research University), Chelyabinsk, Russia
[2]Ural Federal University named after the First President of Russia B.N. Yeltsin, Yekaterinburg, Russia

Abstract

The accuracy of calculating heat exchange by radiation from high-temperature gas flow produced during natural fuels combustion to a large extent depends on the accuracy and status of data on thermophysical properties of gases and the value of the radiative heat flux. The main physical load is carried by the density of the intrinsic heat flux, but all the experimental data on gas mixtures radiation are given as a total emissivity of the components and the mixture in general. That is why this study determines the emissivity factor of carbon dioxide and water vapour as the main constituents of the products of industrial fuel combustion. Dependencies are developed based on reliable experimental data and allowed to perform emissivity factor calculations for the products of combustion. The accuracy of calculated approximation is determined for experimental data in the field of two factors: optical density of gas, and its temperature. The study results are recommended to be used for developing heat exchange calculation programs.

Keywords: emissivity factor, radiation flux, temperature, carbon dioxide, water vapour

Corresponding Author:
E. V. Toropov
evtor@mail.ru

Received: 6 June 2018
Accepted: 15 June 2018
Published: 17 July 2018

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the TIM'2018 Conference Committee.

1. Introduction

While developing mathematical models of complex heat-and-power and heat-engineering systems operating at the temperatures of 1000...2000 K, it is necessary to adapt separate experimental data on radiation of components in various proportions composing the combustion products. Similar tasks arise during designing high-temperature units, their testing and modelling when transiting to a new technological and production level [1, 2]. These considerations define the relevance of the set task.

How to cite this article: E. V. Toropov, L. E. Lymbina, and Yu. G. Yaroshenko, (2018), "Adaptation of Radiative Properties of the End Products of Fuels Combustion within the Temperature Range of 1,000...2,000 K" in *VII All- Russian Scientific and Practical Conference of Students, Graduate Students and Young Scientists on "Heat Engineering and Computer Science in Education, Science and Production"*, KnE Engineering, pages 185–192. DOI 10.18502/keg.v3i5.2668

2. Task Setting, Source Data, Adaptation Method

The experimental data on the density of the intrinsic radiation flux of triatomic components of the products of combustion (CP) of various fuels E_{RO2} and E_{H2O}, W/m^2, as processed by Prof. A.S. Telegin, are given in the form of a table for the combustion products (CP) temperature of 800...1600°C and optical density of the medium from 0,04 to 1,5 in dimensions of 0,01 [$RO_2^{\beta\pi}$]$s_{эф}$ and 0,01[$H_2O^{\beta\pi}$]$s_{эф}$, where the percentage of relevant gases in wet CP is indicated in the brackets [3]. At the fixed atmospheric pressure of 0,1 MPa in the combustion chamber, and switching the percentage to volume ratio of the CP components, the optical density may be input as $l_p = 0,1 r_{RO_2} \cdot s_{эф}$ and $l_p = 0,1 r_{H_2O} \cdot s_{эф}$, meanwhile the actual optical density changes within the range of l_p = 0.004...0.15 MPa·m. The temperature factor also transforms into θ = (t + 273)/100. During formalization of both Table [3] and graphical [4] data, the method of sequential calculation of interpolation coefficients of Gregory–Newton second-order polynomials was used.

3. Emissivity Factor of Carbon Dioxide and Water Vapour

In the coordinate space of $\epsilon_{CO_2} = f\left(l_p, \theta\right)$ the dependency for the carbon dioxide emissivity factor adapted to graphical dependencies of H. Hottel [1, 4] may be represented as a product of three functionals

$$\epsilon_{CO_2} = F_1\left(l_p, \theta\right) \cdot F_2\left(l_p, \theta\right) \cdot F_3\left(l_p, \theta\right), \tag{1}$$

where

$$F_1\left(l_p, \theta\right) = f_1(\theta) + F_4\left(l_p, \theta\right) + F_5\left(l_p, \theta\right), \tag{2}$$

$$f_1(\theta) = 23,01624824 - 2,061531740\theta + 0,0487715480\theta^2, \tag{3}$$

$$F_4\left(l_p, \theta\right) = l_p\left(-598,3855576 + 58,353337220\theta - 1,4723062870\theta^2\right), \tag{4}$$

$$F_5\left(l_p, \theta\right) = l_p^2\left(3031,557034 - 299,10838560\theta + 7,6225203410\theta^2\right), \tag{5}$$

$$F_2\left(l_p, \theta\right) = l^{m_1}, \text{ where } m_1 = 0.97 - 0.01875\theta, \tag{6}$$

$$F_3\left(l_p,\theta\right)=\theta^{-n_1},\ \text{where } n_1=0.004775+0.01892 l_p. \tag{7}$$

The calculation of CO_2 emissivity factor as an example for l_p = 0.04 and θ = 13.73 (t = 1.100°C) gives a deviation from H. Hottel data Δ = – 0.12 % and $E_{CO_2}=\epsilon_{CO_2}\cdot 5,67\theta^4=3\cdot 10^4$ W/m^2 at $\epsilon_{CO_2}=0,149$. The determined negligible error provides for accuracy of representing H. Hottel data in the form of dependencies (1–7).

Similar to dependencies (1–7), for water vapours emissivity factor ϵ_{H_2O} the following calculation formulas were obtained

$$\epsilon_{_2}=F_1\left(l_p,\theta\right)\cdot F_2\left(l_p,\theta\right)\cdot F_3\left(l_p,\theta\right), \tag{8}$$

where

$$F_1\left(l_p,\theta\right)=F_4\left(l_p,\theta\right)\cdot F_5\left(l_p,\theta\right), \tag{9}$$

$$F_4\left(l_p,\theta\right)=\theta^{n_2}, \tag{10}$$

$$F_5\left(l_p,\theta\right)=l_p^{m_2}. \tag{11}$$

In the expressions (8–11) the following denominations were introduced

$$\begin{aligned} n_2 &= 0,210867479-0,018431520\theta+0,438195\cdot 10^{-3}\theta^2+ \\ &+l_p\left(11,65974412-0,7493014050\theta+0,015518990\theta^2\right)+ \\ &+l_p^2\left(-56,31783769+3,7921328740\theta-0,0788911460\theta^2\right), \end{aligned} \tag{12}$$

$$\begin{aligned} m_2 &= 0,210866252+11,65976569 l_p-56,3179325 l_p^2+ \\ &+\theta\left(0,018431352+0,7493304248 l_p-3,792145187 l_p^2\right)+ \\ &+\theta^2\left(0,438189\cdot 10^{-3}+0,015519068 l_p-0,078891476 l_p^2\right), \end{aligned} \tag{13}$$

$$F_2\left(l_p,\theta\right)=l_p^{a+b\theta+c\theta^2}, \tag{14}$$

where

$$a = 0,147605215 + 7,673860291 l_p - 26,7065922 l_p^2, \tag{15}$$

$$b = -0,012019835 - 0,310332303 l_p + 0,993936103 l_p^2, \tag{16}$$

$$c = 10^{-3}\left(0,269051 + 3,577562 l_p - 7,730533 l_p^2\right). \tag{17}$$

$$F_3\left(l_p, \theta\right) = \theta^{\alpha + \beta l_p + \gamma l_p^2}, \tag{18}$$

where

$$\alpha = 10^{-3}\left(-0,853186 + 5,9850027\theta - 0,269050\theta^2\right), \tag{19}$$

$$\beta = 7,67385869 - 0,3103323707\theta + 0,0035775720\theta^2, \tag{20}$$

$$\gamma = -26,70658468 + 0,9939362790\theta - 0,0077305780\theta^2. \tag{21}$$

The calculation of water vapours emissivity factor for l_p = 0.04 and θ = 12.73 (t = 1,000°C) using the obtained formulas (8–21) leads to deviation from H. Hottel data Δ = – 0.23 % with consideration to the correction factor of water vapour partial pressure β = 1.15 at $\epsilon_{H_2O} = 0,191$ and $E_{H_2O} = 2,8 \cdot 10^4$ W/m^2.

One may suggest that the developed method of two-parameter adaptation allows to accurately present the water vapour emissivity factor as a single dependency in function l_p and θ.

4. Adaptation of D. Edwards' Experimental Data

D. Edwards [5, 6] experimentally determined the emissivity factor for a variety of gases, including $CO_2$and H_2O, what is important for combustion products of organic fuels used in heat-and-power and industrial heat-engineering sector; the experimental unit allowed to determine the total emissivity. The experimental unit comprised all the necessary appliances and equipment, providing for the required accuracy of measurement of the spectrum density of the radiative flux. The experiments' results are given as graphs in the field of logarithmic coordinates as per *x*-axis and *y*-axis, what somewhat encumbers the comparative analysis [7, 8].

The results of processing the D. Edwards data on CO_2 emissivity factor using the two-parameter scheme may be presented as a sum of two functionals

$$\epsilon_{CO_2} = F_1\left(l_p\right) - F_2\left(l_p\right)\cdot 10^{-3}T, \tag{22}$$

where

$$F_1\left(l_p\right) = 0,10604136 + 2,775092225 l_p - 8,858008562 l_p^2, \tag{23}$$

$$F_2\left(l_p\right) = 0,033272654 + 0,132336726 l_p + 2,298471747 l_p^2. \tag{24}$$

Similar dependencies were obtained for the emissivity factor for H_2O vapours

$$\epsilon_{H_2O} = F_3\left(l_p\right) - F_4\left(l_p\right)\cdot 10^{-3}T, \tag{25}$$

where

$$F_3\left(l_p\right) = 0,083848783 + 9,220363569 l_p - 45,64014769 l_p^2, \tag{26}$$

$$F_4\left(l_p\right) = 0,037199683 + 0,7150948399 l_p - 3,753951627 l_p^2. \tag{27}$$

The dada on the emissivity factor for CO_2 conform well with H. Hottel data, the deviation does not exceed + 4,0%, increasing to small values of l_p and to low temperatures $T \approx 1000$ K. The dada on the emissivity factor for H_2O differ from H. Hottel data by the value reaching + 40%, increasing in the range of small values of $l_p \approx 0{,}004$ MPa·m and high temperatures $T \approx 2000$ K, what to a large extent may be explained by the error during extrapolation of the testing data, as well as by deviation of H_2O radiation from the Beer's law.

With consideration to these corrections, it is possible to calculate the density of the intrinsic radiation flux for CO_2 and H_2O using one and the same dependency

$$E = \epsilon C_0\left(\frac{T}{100}\right)^4, \tag{28}$$

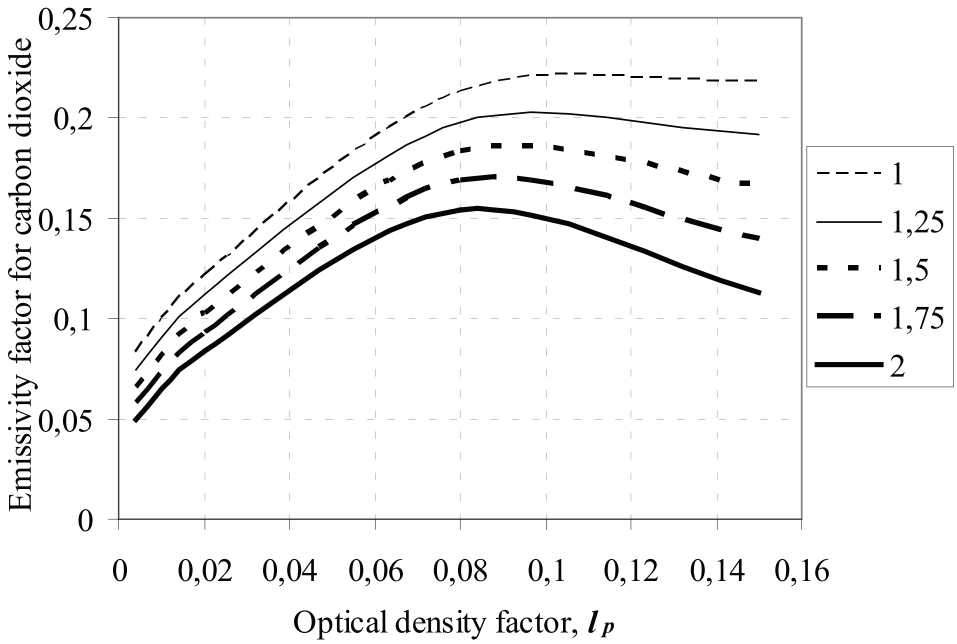

Figure 1: Emissivity factor for CO_2 in the function of the medium's optical density factor l_p at the temperature variation of $10^{-3}T$ (at parameter 1,5, the temperature of T = 1500 K, etc.).

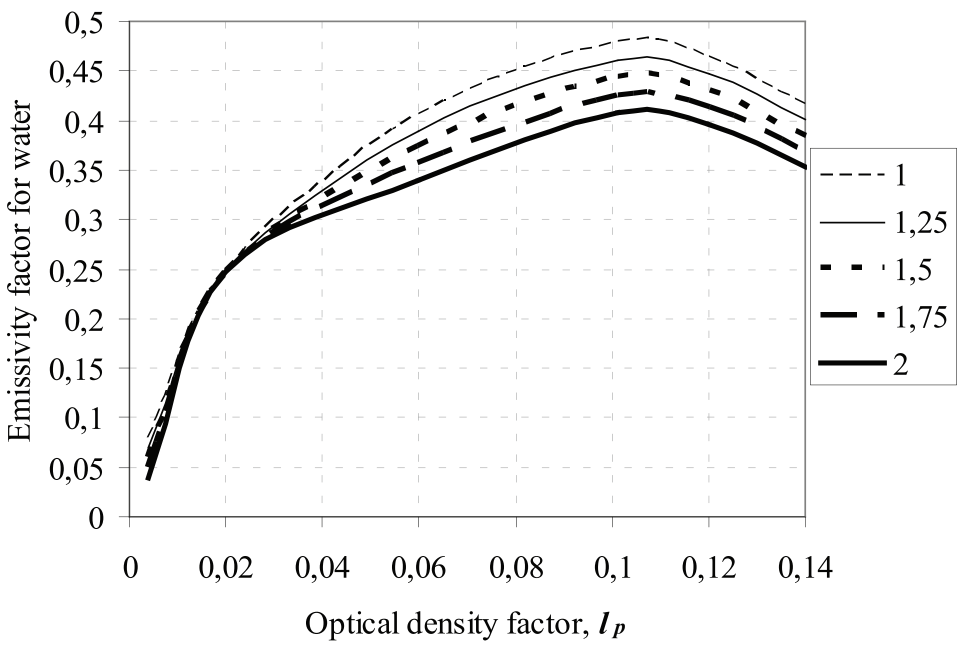

Figure 2: Emissivity factor for H_2O in the function of the medium's optical density factor l_p at the temperature variation of 10^{-3}T (at parameter 1,75, the temperature of 1750 K, etc.).

where C_0 = 5.67 W/m^{2}K^4 is the blackbody coefficient; to determine the emissivity factor of a mixture of vapours of CO_2 and H_2O, the following dependency is used

$$\epsilon_3 = \epsilon_{CO_2} + \epsilon_{_2} - \epsilon_{CO_2} \cdot \epsilon_{_2}. \tag{29}$$

The data for the emissivity factor for carbon dioxide CO_2 and water vapour H_2O calculated using dependencies (22–27) according to the experiments of Edwards, are depicted in Figures 1 and 2.

The character of variation of the emissivity factor in the graphs of Figures 1 and 2 confirms the thesis that describing these dependencies by a simple power formula is not quite accurate [9–14].

The results of adaptation, the accuracy and possible errors of which are defined, may be reflected in the main conclusions.

5. Conclusions

As a result of the analytical work performed on the experimental data on the emissivity factor of industrial gases, dependencies were obtained, which allow to use them in computer analysis. The two-parameter analysis scheme was based on the experimental data of H. Hottel and D. Edwards; a comparative analysis of the results of calculations as per formulas based on these experiments' data was performed.

At high values of the optical density of gases l_p > 0.01 MPa·m the emissivity factor of carbon dioxide is higher than the same factor for water vapours; at low values of l_p < 0.01 MPa·m, water vapour radiation prevails. The method's errors were determined, and the limits of permissible extrapolation were explained in the field of two main factors: optical density of the radiative flux and gas temperature.

References

[1] Telegin, A. C., Shvydky, V. S., and Yaroshenko, Yu. G. (2002). *Heat-mass Transfer* (2nd edition). Moscow: Akademkniga.

[2] Shvydky, V. S., Spirin, N. A., Ladygichev, M. G., et al. (1999). *Elements of the Theory of Systems and Numerical Methods for Modeling the Processes of Heat and Mass Transfer*. Moscow: Internet Engineering.

[3] Zobnin, B. F., Kazyayev, M. D., Kitaev, B. I., et al. (1982). *Thermal Engineering Calculations of Metallurgical Furnaces*. Moscow: Metallurgy.

[4] Blokh, A. G. (1984). *Heat Exchange in the Furnaces of Steam Boilers*. Leningrad: Energoatomizdat.

[5] Petuhova, B. S. and Shikova, V. K. (1987). Reference Book on Heat Exchangers, vol. 2; vol.1 (Russ.). Moscow: Energoatomizdat.

[6] Edwards, D. K., (1976). Thermal radiation measurements, in E. R. G. Eckert and R. J. Goldstein (eds.) *Measurements in Heat Transfer*, chapter 9. Washington, D. C.: Hemisphere.

[7] Gordon, Y. M. and Toropov, E. V. (2013). Scale-up problems of new alternative pyrometallurgical technologies, Energy and resource saving in heat and power engineering and social sphere (materials of the International scientific and technical conference of students, post-graduate students, scientists), pp. 5–12. Chelyabinsk: Publishing Center of SUSU.

[8] Toropov, E. V. (2016). The systemically structured adaptation of heat transfer in boilers. *Bulletin of South Ural State University, Series—Power Engineering*, vol. 16, no. 1, pp. 19–23.

[9] Sparrow, E. M. and Sess, R. D. (1971). *Heat Exchange By Radiation*. Leningrad: Energy.

[10] Kutateladze, S. S. (1990). *Heat Transfer and Hydrodynamic Resistance* (reference book), Moscow: Energoatomizdat.

[11] Khrustalev, B. M., et al. (2007). *Heat and Mass Transfer*, in A. Nesenchuk (ed.), vol. 2, vol. 1. Minsk: Belarusian National University.

[12] Pomerantsev, V. V., Arefiev, K. M., Akhmedov, D. B. et al. (1986). *Fundamentals of the Practical Theory of Combustion*, in V. V. Pomerantseva (ed.). Leningrad: Energoatomizdat.

[13] Shvydky, M., Ladygichev, G., and Shavrin, V. S. (2001). *Mathematical Methods of Thermophysics*. Moscow: Mechanical Engineering.

[14] Blokh, A. G., Zhuravlev, Yu. A., and Ryzhkov, A. N., (1991). *Radiation Heat Transfer* (reference book). Energoatomizdat: Energoatomizdat.