THERMAL RADIATION ABSORPTION IN FUEL DROPLETS

W. A. Abdelghaffar, A.E. Elwardany, M. M. El-kassaby
Mechanical Engineering Department, Faculty of Engineering, Alexandria University,
Alexandria 21544, Egypt

ABSTRACT

The values of the indices of absorption of gasoline fuel (BP Pump Grade 95 RON ULG), 2,2,4-trimethylpentane $(CH_3)_2CHCH_2C(CH_3)_3$ (iso-octane), 3-pentanone $CH_3CH_2COCH_2CH_3$, low sulphur ESSO AF1313 diesel fuel and BP Ford reference diesel fuel are calculated based on the measured values of absorption coefficients. These values are generally lower for pure substances (e.g. 2,2,4-trimethylpentane and 3-pentanone) than for diesel and gasoline fuels. The values of the average absorption efficiency factor for all fuels are approximated by a polynomial function $\sum_{i=0}^{N} A_i R_d^i$, where R_d is the droplet radius and N = 3. Explicit expressions for A_i are derived in a realistic droplet radii range (2- 200 μm) and radiation temperature ranges (1000 K-3000 K) for all types of fuel. This new approximation is shown to be more accurate, compared with the power function aR_d^b where a and b are approximated by quadratic or fourth power polynomials of the radiation temperature with the coefficients calculated in the whole range 2 – 200 μm[1,2], and comparable with the power function aR_d^b, where a and b are approximated by piecewise quadratic functions of the radiation temperature θ_R, with the coefficients calculated separately in the ranges 2 – 5 μm, 5 – 50 μm, 50 – 100 μm and 100 – 200 μm for all fuels[3].

The focus of this paper will be on the models for radiative heating of fuel droplets, which take into account the semi-transparency of droplets in the infrared range, but not the distribution of radiation absorption inside droplets and more specifically on further development of the approach suggested in[1,2,3]. Detailed Mie calculations were replaced by the approximation of the absorption efficiency factor for droplets with an analytical formula aR_d^b, where R_d is the droplet radius, a and b are polynomials (quadratic functions in most cases) of radiation temperature (temperature responsible for radiative heating of droplets). The coefficients of these polynomials were obtained by comparison with rigorous calculations for realistic fuel droplets, assuming that these droplets are irradiated by black-body thermal radiation. This model allowed the authors to attain a reasonable compromise between accuracy and computational efficiency. This is particularly important for the implementation of the thermal radiation model into multidimensional computational fluid dynamics (CFD) codes designed to simulate combustion processes in internal combustion engines. In the model developed in [2], the accuracy of the approximation of the absorption efficiency factor was shown to be rather poor when the range of droplet radii was large (typical values of droplet radii in diesel engines are in the range 2 – 200 μm). Although this shortcoming was overcome in the model developed in [3], where a and b in turn are approximated by piecewise quadratic functions of the radiation temperature, with the coefficient calculated separately in the ranges 2 -5 μm, 5 – 50 μm, 50 – 100 μm and 100 - 200 μm for fuel droplet, this was achieved by increasing the complexity of the model. Finding a compromise between the complexity of the model and its accuracy is the essential precondition for successful modelling. This is the main focus of the present paper.

The following fuels will be used in the present study: low sulphur ESSO AF1313 diesel fuel, BP Ford reference diesel fuel, gasoline fuel (BP Pump Grade 95 RON ULG), iso-octane and 3-pentanone.

Following [4] the averaged (over wavelengths) absorption efficiency factor of droplets is calculated as:

$$\overline{Q}_a = \frac{4n}{(n+1)^2}\left[1-\frac{\int_{\lambda_1}^{\lambda_2}\frac{\exp(\frac{-8\pi\kappa R_{di}}{\lambda})}{\lambda^5[\exp(C_2/(\lambda\theta_R))-1]}d\lambda}{\int_{\lambda_1}^{\lambda_2}\frac{d\lambda}{\lambda^5[\exp(C_2/(\lambda\theta_R))-1]}}\right] \quad (1)$$

where C_2 = 1.439 $\times 10^4$ μm.K, θ_R is the radiation temperature.
Taking into account the experimentally measured values of $\kappa(\lambda)$[1,2,3], it was found that the best approximation for $\overline{Q}_a$ in the ranges $2 \le R_d \le 200\,\mu$m and $1000 \le \theta_R \le 3000$ K is the following:

$$\Lambda = \sum_{i=0}^{N} A_i R_d^i \quad (2)$$

where N = 3 and A_i are approximated as:

$$\Lambda = \sum_{i=0}^{3} a_i \theta_R^i \quad (3)$$

The approximation presented in Eq. (2) is different than the power approximation ($\Lambda = aR_d^b$) developed in [1, 2, 3]. Approximation (2) is used for the entire range of droplet radii (2-200μm). We calculated the coefficients a_i in this range of R_d and various fuels.

The values of Λ predicted based on (Eq. (2)), quadratic and fourth power approximations of coefficients a and b[2], the piecewise quadratic approximation of these coefficients[3] and $\overline{Q}_a$ predicted by Eq. (1) are shown in Fig. 1 for the range of droplet radii 2 – 200 μm. The low sulphur ESSO AF1313 unboiled diesel fuel was used. It can be noticed that the results based on Eq. (2) are more accurate than those based on the quadratic and the fourth power approximations of the coefficients a and b in the entire range of droplet radii, and are comparable with those which follow from the power approximation for these coefficient based on the piecewise approximation. It can also be noticed that the values of $\overline{Q}_a$ decrease with increasing radiation temperature in agreement with the results reported earlier[1, 2, 3].

The results of the average errors of the power approximation for the coefficient a and b, based on piecewise approximation[3], the quadratic and the fourth power approximation[2], and the polynomial approximation based on Eq. (2) showed that the average error of the polynomial approximation is less than that for the power approximation for coefficient based on the quadratic and fourth power approximation in the whole range of droplet radii by more than an order of magnitude. This error is comparable to the error of the piecewise approximation for most fuels. The polynomial approximation for coefficient A_i is expected to be particularly useful for practical engineering applications, including computational fluid dynamics (CFD) codes, as it is more accurate than the power approximation for the coefficients based on the quadratic and fourth power approximations in the entire range of droplet radii, and easier for implementation

into these codes than the piecewise approximation (one correlation for the entire range of droplet radii is required).

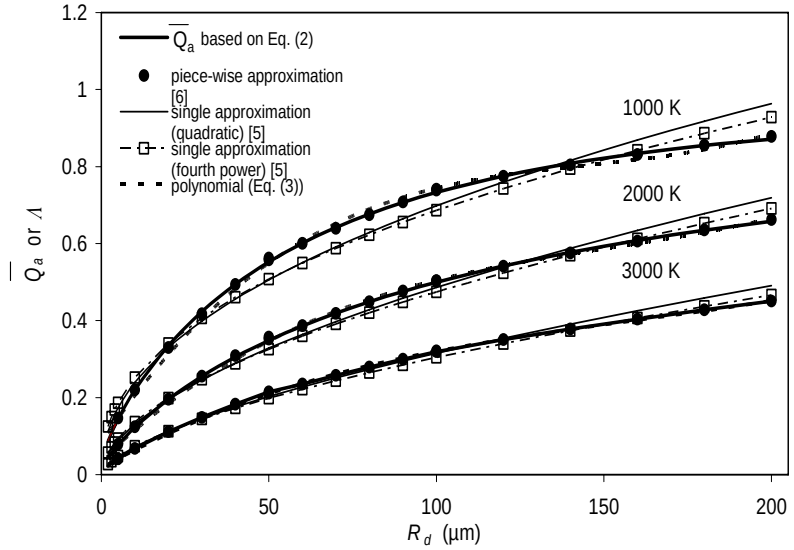

Fig. 1. Plots $\overline{Q}_a$ and its four approximations Λ versus droplet radii for diesel fuel. Three radiation temperatures, 1000 K, 2000 K and 3000 K, are indicated near the curves.

Diesel fuel droplet radii and surface temperatures were estimated to illustrate the effect of thermal radiation on the droplet heating and evaporation. Conditions typical of a diesel engine environment were used. The droplet was irradiated by external thermal radiation from a source at temperature of 2500K. the results showed that the plot calculated using the model based on the polynomial approximation based on Eq. (2) is expected to be more accurate than those calculated based on the quadratic and fourth power approximation of the coefficients *a* and *b*. At the same time, it is close to the plot calculated based on the power approximation for these coefficient based on the piecewise approximation.

It can be concluded that the new approximation has been shown to be more accurate when compared with the approximation aR_d^b with the coefficients *a* and *b* calculated based on quadratic and fourth power approximations of θ_R, whilst it is expected to be more suitable for implementation into computational fluid dynamics (CFD) codes than the one based on the power approximation for coefficients *a* and *b*.

REFERENCES

1. Dombrovsky, L. A., Sazhin, S. S., Sazhina, E. M., Feng, G., Heikal, M. R., Bardsley, M. E. A. and Mikhalovsky, S. V., Heating and evaporation of semi-transparent diesel fuel droplets in the presence of thermal radiation, *Fuel*, Vol. 80(11), pp 1535-1544, 2001.
2. Sazhin, S. S., Abdelghaffar, W. A., Sazhina, E. M., Mikhalovsky, S. V., Meikle, S. T. and Bai, C., Radiative Heating of Semi-Transparent Diesel Fuel Droplets, *ASME Journal of Heat Transfer,* Vol. 126, pp 105-109. Erratum (2004), Vol. 126, pp 490-491, 2004.
3. Sazhin, S. S., Kristyadi, T., Abdelghaffar, W. A., Begg, S., Heikal, M. R., Approximate Analysis of Thermal Radiation Absorption in Fuel Droplets, *Journal of Heat Transfer,* 2007 (In press).
4. Dombrovsky, L. A. A Spectral Model of Absorption and Scattering Thermal Radiation by Diesel Fuel Droplets, *High Temperature*, Vol. 40 (2), pp 242-248, 2002.