# Thermal radiation absorption in fuel droplets

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The values of absorption efficiency factor 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. 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 $\mu$m, and comparable with the power function $aR_d^b$, where $a$ and $b$ are approximated by piecewise quadratic functions of the radiation temperature $\theta_R$, with the coefficients calculated separately in the ranges 2 – 5 $\mu$m, 5 – 50 $\mu$m, 50 – 100 $\mu$m and 100 – 200 $\mu$m for all fuels. This difference in the approximations of the polynomial function and the power function, however, is shown to have little effect on modelling of fuel droplet heating and evaporation in conditions typical for internal combustion engines.

تم حساب قيم كفاءة الامتصاص اعتمادا على قيم معاملات الامتصاص المقاسة عمليا وذلك لوقود الجازولين (أوكتين ٩٥) ووقود أيزواوكتين ووقود ٣ بنتانون ووقود الديزل ذو نسبه الكبريت المنخفضة ووقود الديزل المستخدم فى شركة الوقود البريطانية. القيمة المتوسطة لقيمه معامل كفاءة الامتصاص لجميع أنواع الوقود قربت إلى كثيرة حدود في صورة $\sum_{i=0}^{N} A_i R_d^i$ حيث $R_d$ تمثل نصف قطر قطرة الوقود و $N = 3$ . وتم استنتاج الثوابت $A_i$ لأقطار قطرات من الوقود تتراوح من ٢ إلى ٢٠٠ ميكروميتر ولدرجات حرارة اشعاع ابتداء من ١٠٠٠ إلى ٣٠٠٠ درجه كلفن لجميع أنواع الوقود. وقد أظهرت النتائج ان افتراض القيمة المتوسطة لقيمه معامل كفاءة الامتصاص لجميع أنواع الوقود ككثيرة حدود في صورة $\sum_{i=0}^{N} A_i R_d^i$ يعطى نتائج أكثر دقة عند مقارنتها بفرض أن القيمة المتوسطة لقيمه معامل كفاءة الامتصاص يتغير بصورة آسيه $aR_d^b$ حيث أن الثوابت $a$ و $b$ على شكل معادلة من الدرجة الثانية أو كثيرة حدود من الدرجة الرابعة في درجة حرارة اشعاع فى مدى أقطار قطرات الوقود من ٢ إلى ٢٠٠ ميكروميتر. كما وجد أن معامل الامتصاص بالطريقة المقترحة بهذا البحث متقاربة مع النموذج الذي يفرض أن $a, b$ معادلة من الدرجة الثانية يتغير معاملاتها طبقا لتغير قطر قطرات الوقود فى المدى من ٢-٥ و ٥-٥٠ و ٥٠-١٠٠ و ١٠٠ – ٢٠٠ ميكروميتر وذلك لجميع أنواع الوقود. هذا الفرق بين استخدام فرض المعادلة الأسيه ومعادلة كثيرة الحدود لا يؤثر كثيرا في عمل النماذج الحسابية على تسخين وتبخير قطرات الوقود في ظروف تشغيل آلات الاحتراق الداخلي.

**Keywords:** Absorption efficiency factor, Fuel droplets, Thermal radiation, Heating, Evaporation

## 1. Introduction

The effect of thermal radiation on droplet heating in diesel engines is expected to be particularly strong if the fuel injection takes place at a time when autoignition has already occurred. In this case, the temperature of the remote flame, responsible for droplet radiative heating, is much higher than the ambient gas temperature, responsible for the droplet convective heating [1]. This effect is expected to be strong for droplet heating in gasoline engines as well, when the Gasoline Direct Injection (GDI) system is employed, especially in the stratified operation mode where the

gasoline fuel is injected inside the combustion chamber at the end of the compression stroke. The models for radiative heating of fuel droplets, suggested so far, can be subdivided into three main groups: those which take into account the semi-transparency of droplets in the infrared range and the distribution of radiation absorption inside droplets [2-3], those which take into account the semi-transparency of droplets in the infrared range, but not the distribution of radiation absorption inside droplets [4-6], and those which assume that droplets are gray opaque spheres [7-8]. The second group of models provides a reasonable compromise between accuracy and computer efficiency.

The focus of this paper will be on this particular group and more specifically on further development of the approach suggested in [4-6]. Detailed Mie theory 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 [5], 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 [6], 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.

More advanced models for radiation absorption in diesel fuel droplets which take into account the distribution of absorption inside droplets [2, 3, 9-10] do not seem to be suitable for implementation into CFD codes due to excessive CPU requirements and very small increase in accuracy (see refs. [11-14]).

The present paper will be focused on further studies of the thermal radiation absorption in fuel droplets. The following fuels will be used: low sulphur ESSO AF1313 diesel fuel, BP Ford reference diesel fuel, gasoline fuel (BP Pump Grade 95 RON ULG), iso-octane and 3-pentanone.

The results of the experimental studies of the optical properties of these fuels were originally reported in [5-6].

Firstly, a new approximation for the absorption efficiency factor of all the abovementioned fuels in a wide range of droplet radii is suggested and discussed. Then the results predicted by various approximations are compared. Then the results of application of the new approximation for the efficiency factor of absorption to simulate heating and evaporation of fuel droplets are presented and discussed. Finally, the main results of the paper are summarised.

## 2. Absorption efficiency factor of droplet

Following [5, 15] the absorption efficiency factor of droplets $Q_a$ at a given wavelength $\lambda$ is approximated as:

$$Q_a = \frac{4n}{(n+1)^2}\left[1-\exp(-4kx)\right], \qquad (1)$$

where $x=2\pi R_d/\lambda$ is the droplet diffraction parameter. This equation gives a slightly better approximation for $Q_a$ when compared with that used in [4].

As in [5] we assume that the dependence of radiation intensity on $\lambda$ is close to that of a black body. Using eq. (1) the averaged (over all

wavelengths) absorption efficiency factor of droplets is calculated as:

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

where $C_2$ = 1.439 $\times 10^4$ $\mu$m.K, and $\theta_R$ is the radiation temperature K. This temperature is equal to the external temperature, responsible for radiative heating, in the case of optically thin gas layer and to ambient gas temperature in the case of optically thick gas layer.

Taking into account the experimentally measured values of the function $\kappa$ ($\lambda$), as shown in fig. 1 [5-6], it was found that the best approximation for $\overline{Q}_a$ in the range of droplet radii $2 \le R_d \le 200$ $\mu$m and in the range of radiation temperature $1000 \le \theta_R \le 3000$ K is the following:

$$\Lambda = \sum_{i=0}^{N} A_i R_d^i, \quad (3)$$

where $N$ = 3 and $A_i$ are approximated as:

$$A_i = \sum_{i=0}^{3} a_{ij}\theta_R^j. \quad (4)$$

The approximation presented in eq. (3) is different than the power approximation ($\Lambda = aR_d^b$) developed in [4-6]. Approximation in eq. (3) is used for the entire range of droplet radii (2-200$\mu$m). We calculated the coefficients $a_i$ in this range of $R_d$ and various fuels. The results are shown in table 1.

The predicted values of $\Lambda$ obtained from eq. (3), the suggested approximation in [4-6] and $\overline{Q}_a$ predicted by eq. (2) are compared in the following section.

## 3. Results

The values of $\Lambda$ predicted based on eq. (3), quadratic and fourth power approximations of coefficients $a$ and $b$ [5], the piecewise quadratic approximation of these coefficients [6] and $\overline{Q}_a$ predicted by eq. (2) are shown in fig. 2 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. (3) 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 in [4-6]. Results similar to these shown in fig. 2, but for gasoline and iso-octane fuel, are shown in fig. 3 and 4. The conclusions which follow from these plots are similar to those which follow from fig. 2.

Fig. 1. Indices of absorption of seven types of fuel (low sulphur ESSO AF1313 diesel fuel, unboiled and boiled (Yellow), BP Ford reference diesel fuel used in off road equipment, unboiled and boiled (Pink), gasoline fuel (BP Pump Grade 95 RON ULG), 2,2,4-trimethylpentane (iso-octane) and 3-pentanone versus wavelength $\lambda$. The results for diesel fuels are reproduced from [5] and the results for other fuels are reproduced from [6].

The average errors of the power approximation for the coefficient $a$ and $b$, based on piecewise approximation [6], the quadratic and the fourth power approximation [5], and the polynomial approximation based on eq. (3) are shown in table 2 for radiation temperatures 1000 K, 2000 K and 3000 K and various fuels. The average error of the polynomial approximation is less than that for the power approximation for coefficient based

Table 1
The coefficients $a_i$ calculated for the entire range of $R_d$ (2-200 μm) and various fuel, assuming $N = 3$.

| Type of fuel | $A_i$ | $a_0$ | $a_1$ ($K^{-1}$) | $a_2$ ($K^{-2}$) | $a_3$ ($K^{-3}$) |
|---|---|---|---|---|---|
| Gasoline (BP Pump Grade 95 RON ULG) | $A_0$ | 2.2111885E-02 | -1.1211999E-05 | 1.7793557E-09 | -4.1642522E-14 |
| | $A_1$ | 1.3902902E-02 | 1.2051518E-07 | -1.7353611E-09 | 3.0370578E-13 |
| | $A_2$ | -8.8477132E-05 | 1.4783170E-08 | 5.5106437E-12 | -1.2886977E-15 |
| | $A_3$ | 1.9146314E-07 | -3.8025807E-11 | -1.3291451E-14 | 3.5681599E-18 |
| Diesel (low sulphur ESSO AF 1313) | $A_0$ | 1.5005248E-01 | -7.5862982E-05 | 8.9216488E-09 | 5.5317512E-13 |
| | $A_1$ | 1.7925906E-02 | -4.3758160E-06 | -7.4717615E-10 | 2.5379283E-13 |
| | $A_2$ | -1.2998245E-04 | 4.7779633E-08 | 7.8451155E-14 | -1.4029399E-15 |
| | $A_3$ | 3.0681466E-07 | -1.2047875E-10 | 2.1272634E-15 | 3.1742781E-18 |
| 2,2,4-trimethylpentane (iso-octane) | $A_0$ | 4.5519230E-03 | -2.3855630E-06 | 4.2912271E-10 | -2.0762865E-14 |
| | $A_1$ | 7.8902879E-03 | 1.5803339E-06 | -1.8442659E-09 | 3.0408061E-13 |
| | $A_2$ | -3.5640312E-05 | -1.6384697E-09 | 6.9684132E-12 | -1.3118589E-15 |
| | $A_3$ | 6.8728794E-08 | -7.5925053E-12 | -8.5251891E-15 | 1.8842450E-18 |

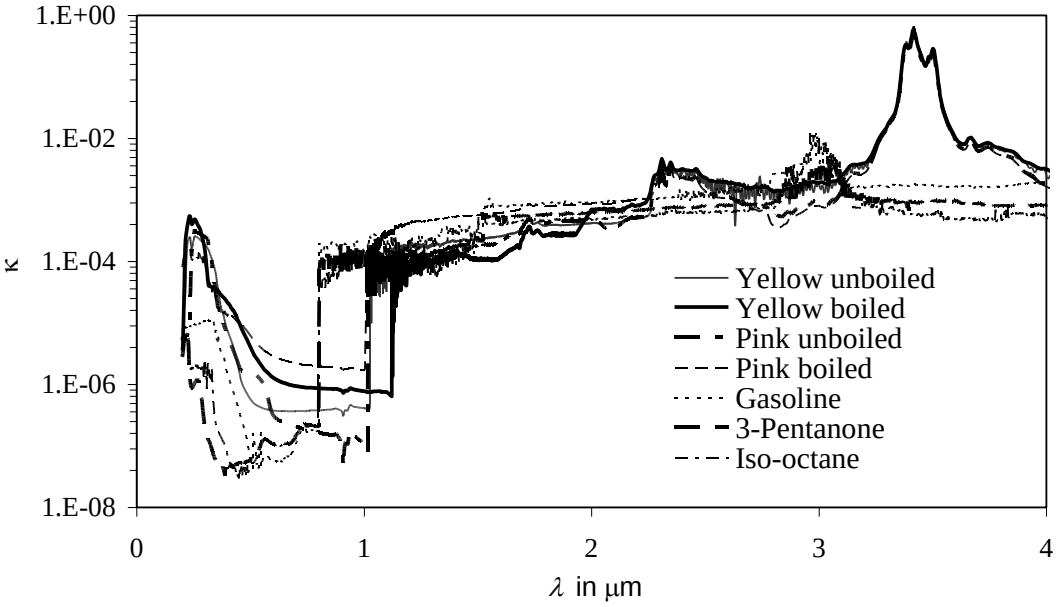


Fig. 1. Indices of absorption of seven types of fuel (low sulphur ESSO AF1313 diesel fuel, unboiled and boiled (Yellow), BP Ford reference diesel fuel used in off road equipment, unboiled and boiled (Pink), gasoline fuel (BP Pump Grade 95 RON ULG), 2,2,4-trimethylpentane (iso-octane) and 3- pentanone versus wavelength $\lambda$. The results for diesel fuels are reproduced from [5] and the results for other fuels are reproduced from [6].

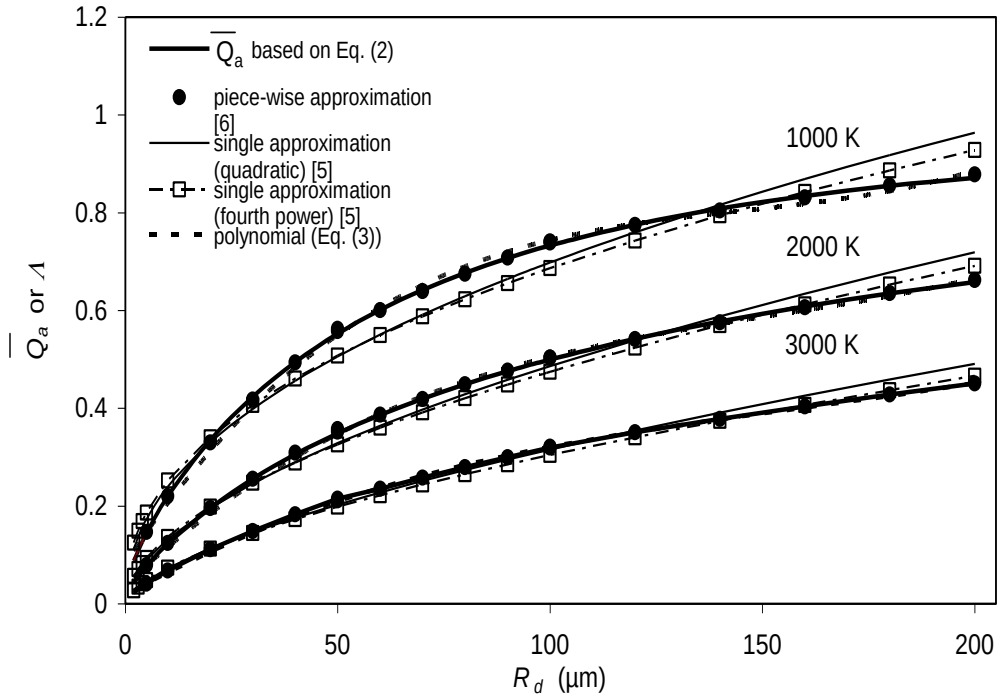


Fig. 2. Plots $\overline{Q}_a$ and its four approximations $\Lambda$ versus droplet radii for diesel fuel. Three radiation temperatures, 1000 K, 2000 K and 3000 K, are indicated near the curves.

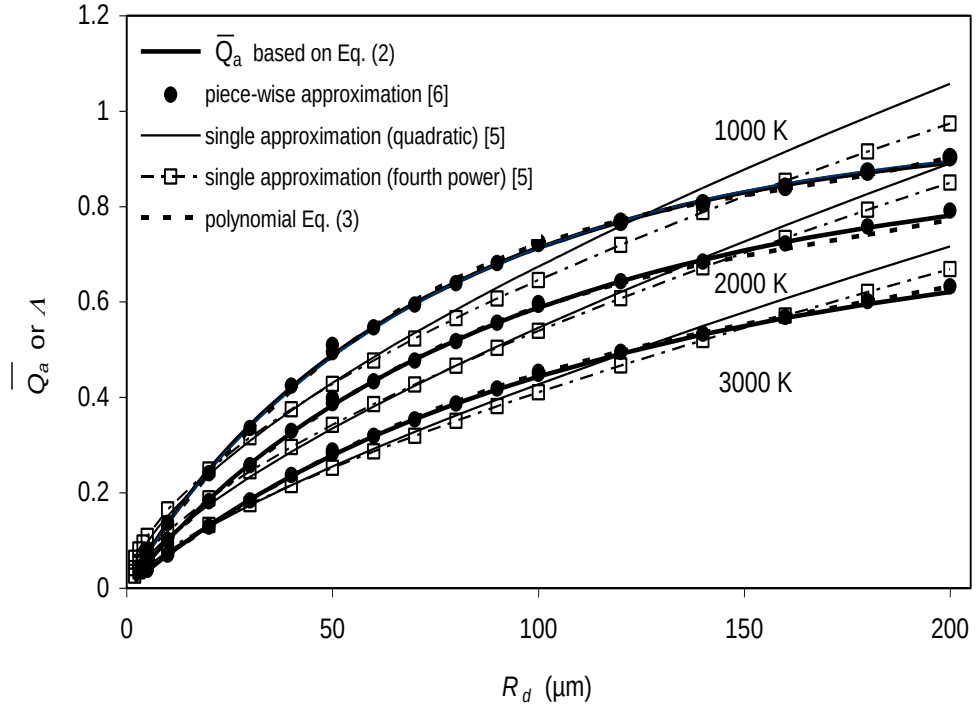


Fig. 3. Plots $\overline{Q}_a$ and its four approximations $\Lambda$ versus droplet radius for gasoline fuel. Three radiation temperatures, 1000 K, 2000 K and 3000 K, are indicated near the curves.

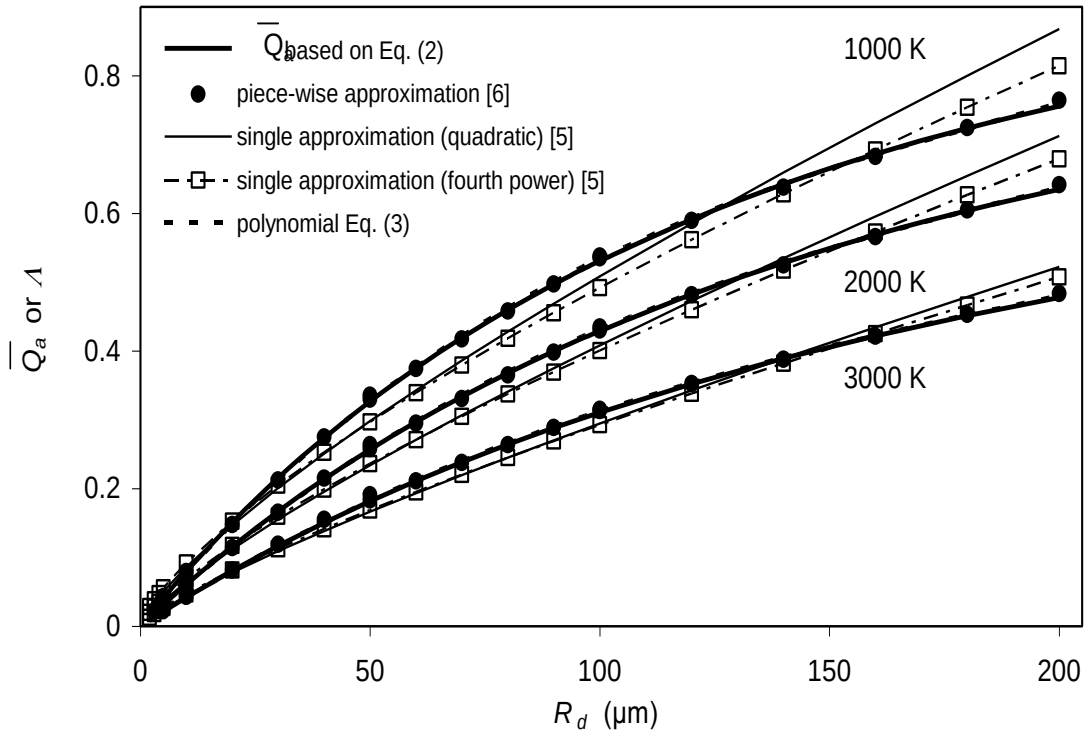


Fig. 4. Plots $\overline{Q}_a$ and its four approximations $\Lambda$ versus droplet radius for iso-octane. Three radiation temperatures, 1000 K, 2000 K and 3000 K, are indicated near the curves.

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 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).

## 4. Applications

Diesel fuel droplet radii and surface temperatures were estimated to illustrate the effect of thermal radiation on these droplet heating and evaporation. Conditions typical of a diesel engine environment were used [16]. A droplet at room temperature ($T_{d0}$= 300 K) and with initial radius equal to 8 μm was injected into air with ambient temperature of 700 K and pressure of 3 MPa. The initial velocity of the droplet was taken to be 1 m/s. The volume of injected liquid fuel was taken as 1 mm$^3$. The volume of air was taken equal to 639 mm$^3$. The volume was calculated using the assumption that if all fuel is evaporated without combusting, the fuel vapour/air mixture becomes stoichiometric [17], assuming that diesel fuel can be approximated by n-dodecane ($C_{12}H_{26}$). The temperature dependence of all transport coefficients and density was taken into account. The relevant approximations are presented and discussed in [17]. The droplet was irradiated by external thermal radiation from a source at temperature of 2500K. The effective thermal conductivity model and gas model, suggested in [18], were used (see [17] for details). Fig. 5 shows the plots of surface temperature ($T_s$) and droplet radius ($R_d$) versus time with and without taking into account the effect of thermal radiation. Thermal radiation is calculated based on the quadratic and fourth

power approximations of the coefficients $a$ and $b$ [5], and the piecewise approximation of these coefficients [6] and the polynomial approximation based on eq. (3). The droplet radius initially increases due to the thermal expansion of liquid fuel then it decreases when the evaporation becomes the dominant. The plot calculated using the model based on the polynomial approximation based on eq. (3) is expected to be more accurate than those calculated based on the quadratic and fourth power approximation of the coefficients $a$ and $b$. It is close to the plot calculated based on the power approximation for these coefficient based on the piecewise approximation.

Plots similar to those shown in fig. 5, but for iso-octane are presented in fig. 6. The droplet was irradiated by external thermal radiation from a source at temperature of 2200K. This is typical for a engine GDI at the stratified operation mode, where the fuel is injected at the end of the compression stroke [19]. The physical properties of iso-octane were discussed in [6]. This fuel was injected into gas volume of 625 mm$^3$. As in the case of fig. 5, the plot calculated using the model based on the polynomial approximation based on eq. (3) is expected to be more accurate than those calculated based on the quadratic and fourth power approximations of the coefficients $a$ and $b$. It is close to the plot calculated based on the power approximation for these coefficient based on the piecewise approximation. The results for the gasoline and 3- pentanone fuel are similar to those shown in figs. 5 and 6.

## 5. Conclusions

Using the measured values of the absorption coefficients for various fuels, the average absorption efficiency factor has been approximated by a polynomial function $\Lambda = \sum_{i=0}^{N} A_i R_d^i$ where $R_d$ is the droplet radius and $N$ = 3. Coefficients $A_i$ have been approximated by cubic polynomials of the radiation temperature $\theta_R$. Coefficients $A_i$ have been calculated in the range of droplet radii 2-200 μm for gasoline fuel (BP Pump Grade 95 RON ULG), 2,2,4- trimethylpentane $(CH_3)_2CHCH_2C(CH_3)_3$ (iso-octane), 3-pentanone $CH_3CH_2COCH_2CH_3$ and low sulphur ESSO AF1313 diesel fuel. This new approximation has been shown to be more accurate when

Table 2
The errors of approximations for $\overline{Q_a}$ in the ranges $2 \le R_d \le 200\,\mu$m and various fuels

| $\Lambda$ | % Average error | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Diesel | | | 2,2,4 Trimethylpentane | | | Gasoline | | |
| | 1000 K | 2000 K | 3000 K | 1000 K | 2000 K | 3000 K | 1000 K | 2000 K | 3000 K |
| Piece-wise | 0.53 | 0.73 | 0.67 | 0.65 | 0.71 | 1.22 | 0.98 | 1.1 | 1.84 |
| Quadratic | 9.92 | 7.46 | 6.26 | 12.94 | 11.14 | 9.87 | 18.55 | 15.56 | 13.81 |
| Fourth power | 12.21 | 9.07 | 7.5 | 16.41 | 14.33 | 12.32 | 23.57 | 20 | 17.16 |
| Polynomial (eq. (3)) | 4 | 3.52 | 3.1 | 1.51 | 1.1 | 0.76 | 3.7 | 2.78 | 2.26 |

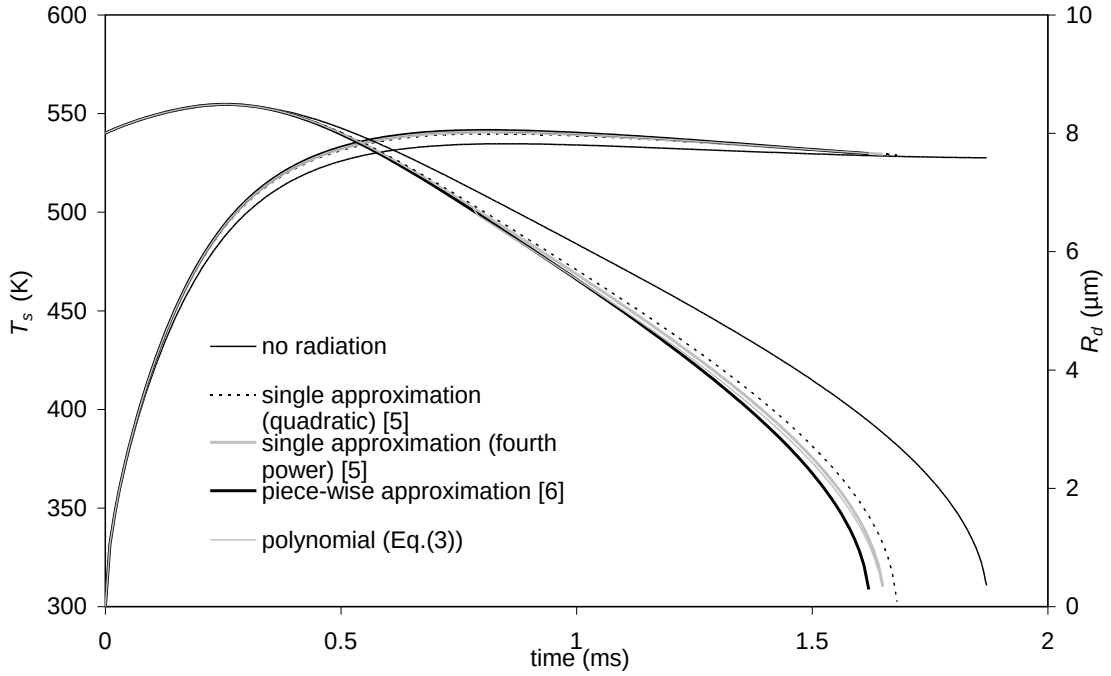


Fig. 5. Plots of *Ts* and *Rd* versus time for a diesel fuel droplet injected into air with initial temperature $Tg0$ = 700 K; the initial droplet temperature is $Td0$ = 300 K, the radiation temperature $\Theta_R$=2500 K and the initial droplet radius $R_{d0}$ = 8 μm.

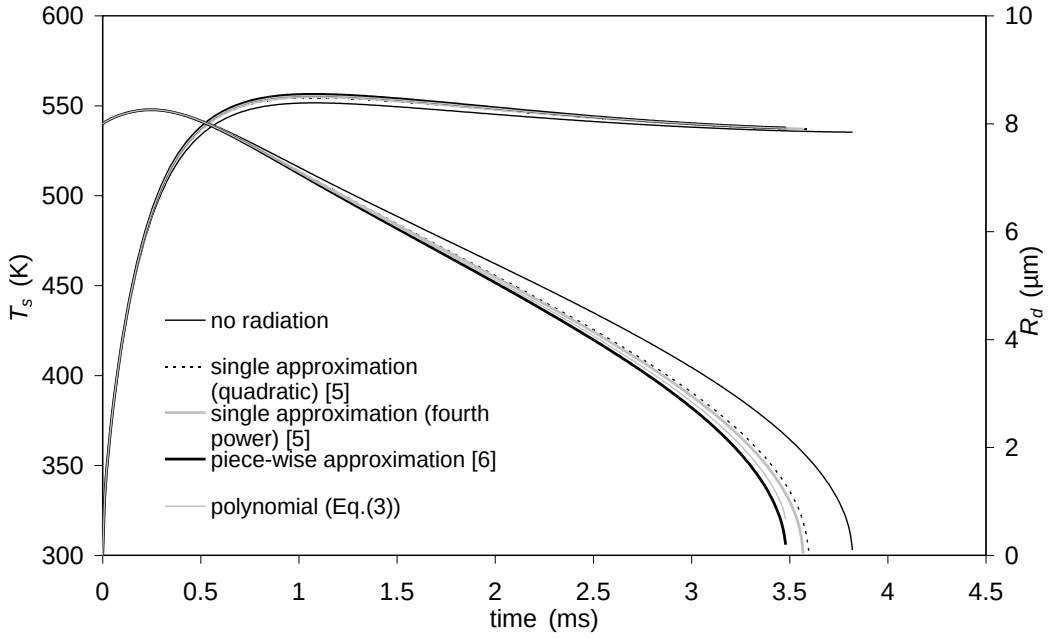


Fig. 6. The same as fig. 5 but for iso-octane and $\Theta_R$ = 2200 K.

compared with the approximation $aR_d^b$ with the coefficients $a$ and $b$ calculated based on quadratic and fourth power approximations of $\theta_R$. The accuracy of the new approximation has been shown to be comparable to the power approximation for these coefficient based on the piecewise approximation. The polynomial approximation, presented in this paper, is expected to be more suitable for implementation into CFD codes than the one based on the power approximation for coefficients $a$ and $b$.

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## Nomenclature

$a_i$ is the coefficient introduced in eq. (4),
$A_i$ is the coefficient introduced in eq. (3),
$C_2$ is the coefficient in the Planck function (μm K),
$n$ is the index of refraction,
$Q_a$ is the absorption efficiency factor,
$R_d$ is the radius of the droplet (m),
$T$ is the temperature, (K), and
$x$ is the droplet diffraction parameter.

## Greek symbols

$\theta_R$ is the radiation temperature, (K),
$k$ is the index of absorption,
$\lambda$ is the wavelength (μm), and
$\Lambda$ is the coefficient introduced in eq. (3).

## Superscripts

— average

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