Bulgarian Chemical Communications, Volume 51, Special Issue A (pp. 224-230) 2019

Fullerene C_{60} conjugated with *N*,*N*-dimethylaniline - a hybrid antioxidant acting at high temperature

R. Czochara, J. Kusio, G. Litwinienko*

University of Warsaw, Faculty of Chemistry, Pasteura 1, 02-093 Warsaw, Poland

Received March 5, 2019; Revised March 14, 2019

Fullerene derivative, *N*-methyl-2-[4-(dimethylamino)phenyl]-3,4-[60]fulleropyrrolidine (**F-DMA**), was prepared and its antioxidant activity was tested by means of Differential Scanning Calorimetry during non-isothermal oxidation of stearic acid (STA) as a model of saturated lipid. Temperature of the start of oxidation and the overall Arrhenius kinetic parameters (activation energy E_a, pre-exponential factor *Z*, and rate constants *k*) of oxidative decomposition indicate that **F-DMA** is effective antioxidant acting at temperatures above 150°C, with temperature of start of oxidation 12-19°C higher and with smaller *k* (two-fold and three-fold at 150 and 200°C, respectively) than for oxidation of non-inhibited pure STA. On the other hand, the experiments with peroxidation of cumene at 30°C indicate that **F-DMA** is not efficient trap for peroxyl radicals (no inhibition or retardation effect). We suggest that **F-DMA** is able to inhibit high temperature STA autoxidation due to trapping alkoxyl radicals by C_{60} core, with additional participation of tertiary amine moieties as chain-breaking agents, whereas autoxidation of cumene is mediated by peroxyl radicals that are not effectively scavenged by any part of **F-DMA**.

Keywords: fullerene, antioxidant, lipids, amines, hydrocarbon oxidation, oxidation kinetics

INTRODUCTION

Peroxidation is a chain reaction mediated by free radicals, proceeding by three main stages, with reactions 1 and 2 as propagation step repeated tens to hundreds times and resulting in the conversion of the organic material into hydroperoxide, LOOH.[1]

$$L^{\bullet}+O_2 \rightarrow LOO^{\bullet} \qquad k_{ox} \sim 10^9\ M^{-1}s^{-1} \quad (1)$$

$$LOO^{\bullet}+L\text{-}H \rightarrow LOOH + L^{\bullet} \qquad k_p < 100\ M^{-1}s^{-1} \quad (2)$$

with the rate law expression for uninhibited peroxidation:

$$-\frac{d[O_2]}{dt} = \frac{k_p}{\sqrt{2k_t}}[LH]\sqrt{R_i} \quad (3)$$

where k_t is rate constant of termination and R_i is the rate of initiation.

Some hydrocarbons undergo peroxidation process mediated by radicals other than alkylperoxyl during the propagation step. The examples of such mechanisms are processes occurring under low partial pressures of oxygen or at higher temperatures, when thermal cleavage or metal ions cause decomposition of the primary products (hydroperoxides, LOOH). Very recent series of papers published by Coote *et al.*[2-4] indicate that autoxidation of saturated hydrocarbons/polymers at elevated temperatures is propagated by alkoxyl radicals as thermodynamically more stable intermediates formed by decomposition of tetraoxides (products of square termination of alkylperoxyls).

Regardless the nature of the propagating radicals, a very important problem is to stop the propagation in order to protect organic materials against oxidation and deterioration. This can be realized by reduction of the propagating radicals ($Y^{\bullet}$ = $LOO^{\bullet}$, $LO^{\bullet}$) to relatively stable radicals, or to non-radical products, or by formation of non-reactive adducts. All three kinds of reactions are schematically shown as reactions (4-6).

$$Y^{\bullet}+ CBA \rightarrow Y\text{-}H + CBA_{(red)}^{\bullet} \quad (4)$$

$$Y^{\bullet}+ CBA_{(red)}^{\bullet} \rightarrow Y\text{-}CBA \quad (5)$$

$$Y^{\bullet}+ CBA \rightarrow (Y\text{-}CBA)^{\bullet} \quad (6)$$

Several classes of non-phenolic antioxidants have been reviewed by Foti and Amorati[5], and the mechanisms of their reaction with radicals were grouped into: (i) formal H-atom donation from X-H bonds, where X = heteroatom, reaction 4 (as in the case of ascorbic acid, uric acid, bilirubin and thiols), (ii) addition reactions to polyunsaturated systems with formation of C-radicals poorly reactive towards O_2, for example β-carotene and all carotenoids (reaction 6), (iii) co-oxidation processes characterized by fast cross-termination reactions, for example γ-terpinene, and (iv) catalytic quenching of superoxide as Superoxide Dismutase (SOD) mimics. It seems that fullerenes, with their ability to form adducts with unusually high number of benzyl, methyl and other alkyl radicals per single C_{60} molecule (and called the radical sponge)[6-10], could be efficient chain breaking antioxidants. Reactions of C_{60} with those radicals are fast and lead to the formation of stable

* To whom all correspondence should be sent:
E-mail:litwin@chem.uw.edu.pl

radicals with electrons delocalized over the whole sphere of fullerene. However, experiments in model system with styrene autoxidation indicated that the rate of reaction of pristine C_{60} with styrylperoxyl radical is not enough to effectively compete with propagation process (k_{inh} should be at least two orders of magnitude bigger than k_p) and C_{60} is not a good chain-breaking antioxidant.[11] On the other hand, fullerene conjugated with derivatives of phenolic antioxidant (like 2,6-di-*tert*-4-methylphenol, BHT) behaved as typical chain breaking antioxidants.[11] Taking into account the results reported by various research teams and basing on our previous results indicating that pristine fullerene is effective inhibitor of oxidation carried out at higher temperatures [12-14], we proposed a series of new hybrid antioxidants with phenolic moiety covalently bonded to C_{60} sphere. We demonstrated that such antioxidants are more active than the building blocks (pristine C_{60} and phenols) used separately and, presumably, the phenol moieties are responsible for reaction with peroxyl radicals while C_{60} core is responsible for scavenging of radical species generated at higher temperatures in the oxygen poor systems.

In the preceding publication we described the inhibitory effect of C_{60} conjugated with hydroxychromane (analogue of α-tocopherol) during non-isothermal oxidation of stearic acid, STA, and linolenic acid, LNA. In saturated hydrocarbons the hybrid C_{60}+hydroxychromane derivative was effective antioxidant for STA, acting at temperatures above 150°C, expressed as 9 kJ/mol increase of E_a and values k twice smaller than for oxidation of non-inhibited pure STA. However, experiments with LNA oxidized at temperatures starting at 80°C indicate that hybrid derivative did not improve the oxidative stability of polyunsaturated lipids (E_a, Z and k's were almost the same as for oxidation of pure LNA). We suggest that C_{60} is able to inhibit STA autoxidation due to formation of thermally stable adducts with alkoxyl radicals whereas autoxidation LNA is mediated by peroxyl radicals that are not effectively scavenged by C_{60}.[15]

In this work we are testing the antioxidant activity of C_{60} with covalently bonded derivative of *N*,*N*-dimethylaniline. Such hybrid is interesting for two reasons: there is no H atom to be abstracted as in conventional phenolic or amine antioxidants, therefore we can exclude the effect described by Foti and Amorati as type (i) and eventual anti-radical activity could be interpreted as addition of a propagating radical to fullerene core or other cross-termination effects resulting in suppression of peroxidation. We synthesized *N*-methyl-2-[4-(dimethylamino)phenyl]-3,4-[60]fulleropyrrolidine, a derivative of C_{60} with covalently bonded dimethylamine moiety attached to the carbon sphere via *N*-methylpirrolidine ring. The structure of this derivative (acronym: **F-DMA**) together with structure of *N*-methylfullero-pyrrolidine (C_{60}-Py) are presented in Figure 1.

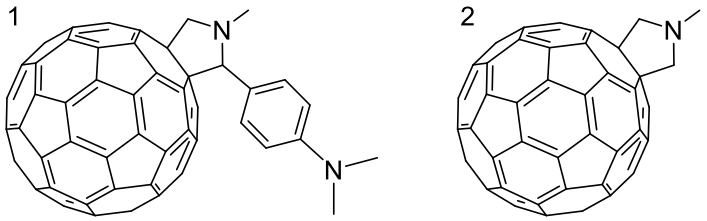


Figure 1. Structure of compounds: 1: **F-DMA**, 2: C_{60}-Py.

EXPERIMENTAL

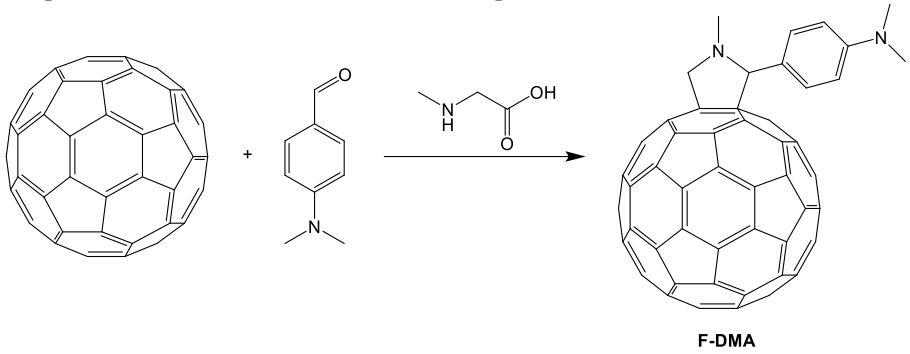
Stearic acid, STA, (99%, Sigma-Aldrich) was stored at 0°C in darkness. Fullerene C_{60} was of 99+% purity (MER Corporation, Tucson). 4-(dimethylamino)benzaldehyde, *N*-methylglycine (Sarcosine™), and solvents were purchased from Sigma-Aldrich. Cyclohexane and toluene were dried and distilled before use, other solvents were analytical grade reagents and were used as received. ^{1}H and ^{13}C NMR spectra were recorded using Varian 300 MHz instruments.

Oxidation of STA monitored by Differential Scanning Calorimetry (Du Pont 910 apparatus with Du Pont 9900 thermal analyzer and normal pressure, recently refurbished cell was used). Temperature and cell constant were calibrated with ultrapure indium standard. TA Instruments software (General V4.01) was used for collecting the data and for determination of temperatures from DSC curves. The oxidations were performed under oxygen flow 6 dm^3/h. Samples (3.0-3.5 mg) were heated from 50 to 250°C in open aluminium pan with linear heating rate β (2.5; 5.0; 7.5; 10.0; 12.5;

15.0; 17.5; 20.0 K/min). As a reference material an empty aluminium pan was used.

Progress of isothermal (30°C) oxidation of cumene was performed in the two-channel gas uptake apparatus with differential pressure sensor (pressure transducer)[16] by measuring the changes of pressure of oxygen between sample and reference twin flasks (5 mL each). In both flasks 2.00 mL of cumene and 2.00 mL of 0.1 M 2,2′-azobis(2-methylpropionitrile) solution in chlorobenzene were placed. For inhibition studies, the sample flask contained 14.4 μM of **F-DMA** (injected as 50 μl of 1.16 mM **F-DMA** solution in benzonitrile), in contrast to reference flask with high concentration of 2,2,5,7,8-pentamethyl-6-hydroxychromane (PMHC, 50 μM of 2×10^{-2} M solution) in order to completely inhibit oxidation in reference material. The rate of initiation determined in the independent experiments with PMHC as standard antioxidant was $R_i = 4.56$ nMs^{-1}.

Synthesis route for derivative **F-DMA** is depicted in Scheme 1.



Scheme 1. Synthesis of fullerene derivative **F-DMA**.

Fullerene derivative **F-DMA** was obtained using particular type of 1,3-dipolar cycloaddition of azomethine ylides to olefins, known as Prato reaction, described in our previous paper.[14] C_{60} (300 mg, 0.41 mmol), *N*-methylglycine (192 mg, 2.16 mmol) and 4-(dimethylamino)benzaldehyde (61 mg, 0.41 mmol) were dissolved in 300 mL of dry toluene. The mixture was stirred and boiled under reflux for 24 h, then cooled down and the solvent was removed using rotary evaporator, under reduced pressure. Obtained residue was purified by flash chromatography (silica gel; cyclohexane:toluene, 1:2, v/v) and the main fraction was analyzed by TLC and GPC-HPLC (Fenogel 50Å, toluene, UV detection at 285 nm) indicating not complete separation of the reaction products in the main fraction (see Figure 2A). Additional purification of the main fraction by flash chromatography on silica gel with $CHCl_3$ as eluent provided pure monoadduct **F-DMA** as a brown solid (158 mg, 39% yield based on converted fullerene) after solvent removal. HPLC analysis confirmed that **F-DMA** has one functional group attached to fullerene core, see Figure 2B. Analysis: ^{1}H NMR (300 MHz, $CDCl_3$, TMS) δ (ppm): 7.78 (d, 2H, ArH) 6.72 (d, 2H, ArH), 3.11 (s, 6H, CH_3), 3.04 – 2.90 (m, 3H, CH_2, CH).

RESULTS AND DISCUSSION

Non isothermal oxidation of lipids and hydrocarbons was the subject of our previous studies resulting in the kinetic parameters for thermal oxidation of saturated [17] and unsaturated [18] fatty acids and their esters, and polymers like high density polyethylene[12]. All those organic materials can be also used as matrices for studies of antioxidant effect of various additives. We also noticed that a very important problem is to fit the mode of antioxidant action to the nature of radicals mediating peroxidation process in bulk phase, that is, some antioxidants effectively protecting polyunsaturated lipids at lower temperatures are not able to inhibit oxidation of saturated lipids and polymers (proceeding at higher temperatures). Phenols are not effective inhibitors of high temperature oxidation for two reasons – usually phenols are too volatile to survive high temperature during longer time, and, second reason is a different mechanism of propagation process occurring at low and high temperatures.[2-4] Therefore, we designed and prepared series of hybrid antioxidants assembled from C_{60} and phenols[13] scavenging broad range of peroxyl, alkoxyl, and alkyl radicals that are involved in propagation step at higher temperatures. In this work we are presenting the results for another kind of hybrid antioxidant built from C_{60} and dimethylphenylamine (**F-DMA**, see Fig.1) as non-phenolic, non-volatile high temperature antioxidant. Both nitrogen atoms in **F-DMA** are methylated, thus, there is no easily abstractable hydrogen from N-H bond in this molecule.

Typical DSC traces for non-isothermal oxidation of STA containing 2 mM of **F-DMA** at heating rates (β) 2.5-20 K/min are presented in Figure 3. Temperature of extrapolated start of oxidation, T_e, was determined as a cross-section of tangents of baseline and thermal peak of oxidation. One can observe the higher β the higher T_e was determined (see also Table 1, the presented values T_e are the mean of at least three measurements). Non-isothermal oxidation of saturated hydrocarbon chain of STA starts at relatively high temperatures (always above 430 K, i.e., 150°C). A comparison of T_e values determined for oxidation of pure stearic acid with the values measured for STA containing 2mM **F-DMA** (for the same β) indicates a significant increase of oxidative stability (12-19°C), defined here as extended range of temperatures without detectable thermal effect of spontaneous oxidation (flat baseline before the onset T_e point).

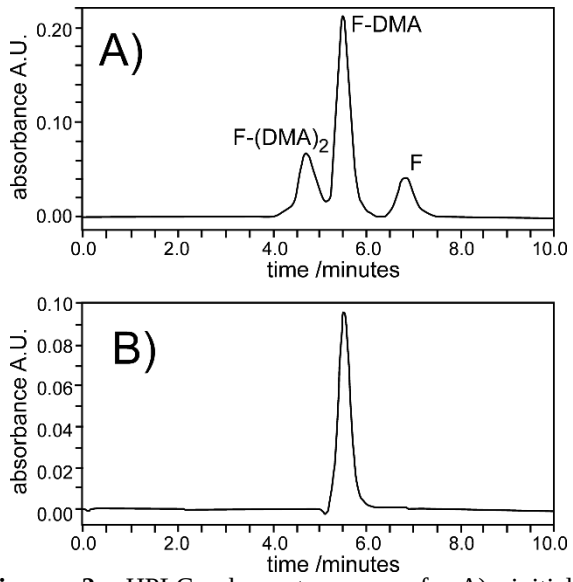


Figure 2. HPLC chromatograms of: A) initially separated product of Prato reaction with unreacted fullerene marked as **F**, monoadduct **F-DMA**, and di-adduct marked as **F-(DMA)2**, B) chromatogram of purified product with the only peak coming from monoadduct **F-DMA**.

A shift of T_e to higher temperatures can be interpreted as antioxidant effect of the additive and such shift corresponds to extension of induction times during other accelerated tests employing the isothermal oxidation for assessment of oxidative stability. **F-DMA** is more efficient than pristine C_{60} and *N*-methyl-3,4-[60]fulleropyrrolidine (C_{60}-Py) used with the same 2 mM concentration, as can be seen in Table 2 presenting the values of T_e determined for three different heating rates.

DSC non-isothermal oxidation mode has advantage over accelerated tests, because the changes of T_e recorded for several different β can be used for calculation of the overall kinetic parameters, activation energy (E_a) and pre-exponential factor (Z) for oxidation processes by the Ozawa-Flynn-Wall's method [12, 17], from the linear dependence:

$$\log \beta = a \times T_e^{-1} + b \qquad (7)$$

where the slope $a = -0.456\, E_a / R$ and intersection $b = -2.315 + \log(ZE_a / R)$, and R is the gas constant (8.314 [J mol^{-1}K^{-1}]).

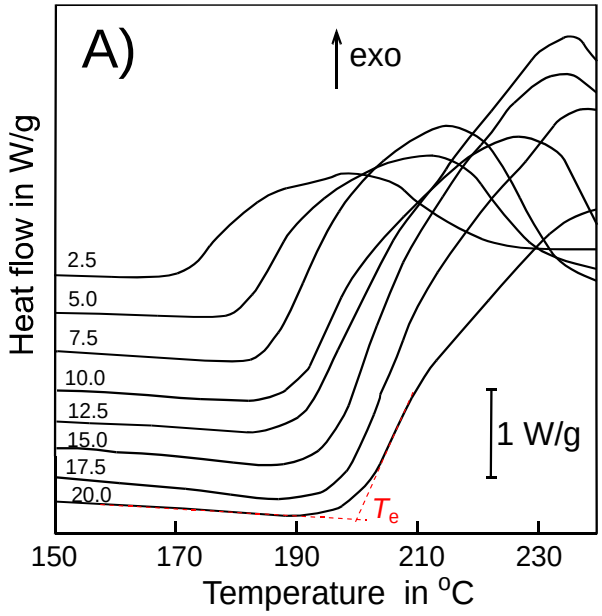


Figure 3. DSC curves of non-isothermal oxidative decomposition of STA containing **F-DMA** ($C_{F\text{-}DMA}$ = 2.0 mM) recorded for linear heating rates β from 2.5 to 20.0 K/min, as indicated over each curve. Curves were shifted vertically for clarity of presentation.

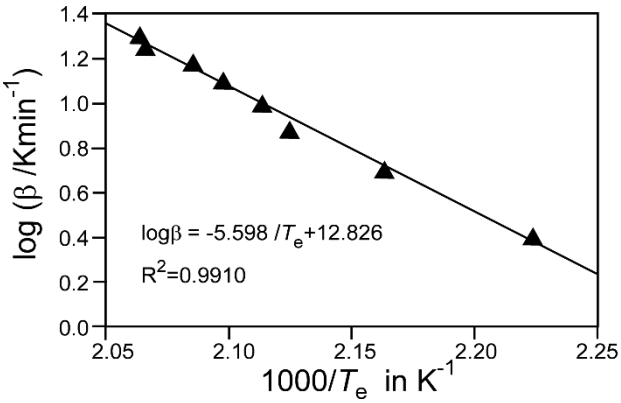


Figure 4. Plot of logβ versus 1000/T_e for oxidation of STA containing 2.0 mM **F-DMA**.

Table 1 contains also the kinetic parameters measured and calculated for oxidation of pure STA reported previously (E_a = 116 ± 8 kJ/mol and Z =

1.34×10^{13} s^{-1}) [15] being in reasonable agreement with the activation energy of isothermal oxidation of saturated fatty acids.[17] The comparison of activation parameters of oxidation shows a decrease of activation barrier from 116 ± 8 kJ/mol for pure STA and to 101 ± 6 kJ/mol for STA with 2 mM **F-DMA**.

Table 1. Temperatures of start of oxidation (T_e) obtained for different heating rates (β), statistical parameters of straight line equation (7), and overall kinetic parameters: E_a - activation energy, Z - pre-exponential factor, k - rate constants obtained for oxidation of pure STA and STA containing 2 mM of derivative **F-DMA**. The errors of E_a were calculated from the standard error σ of the slope a calculated with confidence level 90% ($\sigma_{90\%}$).

Stearic acid (STA)[a]			*STA with 2 mM **F-DMA***		
β [K/min]	T_e [K]	Statistical and kinetic parameters	β [K/min]	T_e [K]	Statistical and kinetic parameters
2.5	437	a = -6.36	2.5	449	a = -5.5981
5.0	447	b = 14.95	5.0	462	b = 12.8260
7.5	452	R^2 = 0.9982	7.5	470	R^2 = 0.9910
10.0	456	E_a = 116 ± 8 kJ/mol	10.0	473	E_a = 101 ± 6 kJ/mol
12.5	458	$Z = 1.34 \times 10^{13}$ min^{-1}	12.5	477	$Z = 1.13 \times 10^{11}$ min^{-1}
15.0	461	$k_{50°C} = 2.50 \times 10^{-6}$ min^{-1}	15.0	479	$k_{50°C} = 6.11 \times 10^{-4}$ min^{-1}
17.5	465	$k_{100°C} = 8.07 \times 10^{-4}$ min^{-1}	17.5	483	$k_{100°C} = 6.11 \times 10^{-4}$ min^{-1}
20.0	466	$k_{150°C} = 6.66 \times 10^{-2}$ min^{-1}	20.0	484	$k_{150°C} = 2.96 \times 10^{-2}$ min^{-1}
		$k_{200°C} = 2.16$ min^{-1}			$k_{200°C} = 0.63$ min^{-1}
		$k_{250°C} = 36.1$ min^{-1}			$k_{250°C} = 7.52$ min^{-1}

[a] Values for pure STA were published in previous report. [13]

Table 2. Comparison of temperatures of start of oxidation of stearic acid (STA) with STA containing 2 mM of: C_{60}, C_{60}-Py, and **F-DMA**. Values for C_{60}, C_{60}-Py were taken from [13].

β [°C/min]	T_e [°C]			
	STA	STA + C_{60} (2 mM)	STA + C_{60}-Py (2 mM)	STA + **F-DMA** (2 mM)
5	174	189	184	189
10	183	197	198	200
15	188	202	203	206

This observation would suggest that **F-DMA** is prooxidant that is counterintuitive conclusion when compared to much higher temperatures of start of oxidation determined for STA stabilized by 2mM **F-DMA** (Table 2). The contradiction is apparent, since the rate constants calculated from the Arrhenius equation:

$$k = Z \exp(-E_a/RT) \quad (8)$$

for temperatures 50-250°C in 50 degrees intervals indicate that, indeed, at temperature 50°C oxidation of STA is slower than STA/**F-DMA**, at 100°C the rate constants are almost the same for both systems, whereas at temperatures above 150°C **F-DMA** becomes an effective antioxidant. There are two possible explanations of such inversion of the oxidation rates for pure STA and STA/**F-DMA** when passing from lower to higher temperature. First one is that temperature of start of oxidation of all studied samples (150-200°C) is above the isokinetic temperature, T_{iso}, the temperature at which two different processes have the same rate constants. Above T_{iso} the process with higher E_a proceeds faster than the process characterized by lower E_a [14,15,18], therefore oxidation rate constants calculated for STA at 150 and 200°C are bigger than for STA/**F-DMA**. This prediction of k (based on E_a and Z) is in agreement with T_e values determined or STA/**F-DMA** that are always higher than T_e values for oxidation of pure STA, see Table 2. The inversion of rate of processes carried out at temperatures below and above T_{iso} is well known phenomena in chemical kinetics, unfortunately, this problem is overlooked in many reports using accelerated tests for oxidative stability,[19] when the results from lower temperatures are compared with the results of experiments performed at higher temperatures and vice versa. In our previous publications we described that this problem was also noticed when two different lipid system were used as matrices for determination of antioxidant activity of various

additives, because oxidation temperatures for saturated STA is 100°C higher than for polyunsaturated fatty acids. Another explanation of different behaviour of some antioxidants is volatility of the additive, however, this can be excluded as **F-DMA** is thermally stable and not volatile at temperatures below 250°C. Additional explanation of the enhanced activity of **F-DMA** at higher temperatures is increasing participation of the scavenging ability C_{60} core in the overall inhibition effect that corresponds to the change of the mechanism of autoxidation at temperature close to 200°C – due to increased participation of alkoxyl radicals (see the Introduction). Although C_{60} do not scavenge peroxyl radicals, it effectively traps alkyl and alkoxyl radicals, thus, preventing the system against re-initiation or branching the kinetic chain of oxidation.

Our results indicate that **F-DMA** is more active than pristine C_{60} and C_{60}-Py (see Table 2). There is no N-H bond that could donate a hydrogen atom to radicals during antioxidant action, however, inhibiting effect of tertiary (alkyl) amines has been reported as becoming significant at higher temperatures[20] because reaction of amine with hydroperoxides and formation of tertiary amine N-oxide: $R_3N+R'OOH\rightarrow (R_3N+R'OOH) \rightarrow R_3NO+R'OH$. In **F-DMA** neither N-oxide formed in pirrolidine nor in dimethylphenylamine sites cannot undergo the Cope elimination (formation of hydroxylamine), however, tertiary N-oxides decompose to secondary amines and, subsequently, to nitroxyls.[21] All three kinds of nitrogen derivatives are non-phenolic antioxidants employed in polymers. Another possible explanation is that H atom is abstracted from methyl or methylene C-H, ie. from dimethylamine group or pirrolidine ring. H atom abstraction from dimethylanilines $(CH_3)_2N$-Ph by model diphenylpicrylhydrazyl radical was described by Baciocchi *et al.* [22]. Basing on deuterium kinetic isotope effect they reported H (or D) atom abstraction via concerted proton electron transfer (CPET). More relevant to our studies are works by Bietti and coworkers on the kinetics of reaction of tertiary amines with benzyloxyl ($PhCH_2O^{\bullet}$) and cumyloxyl ($CumO^{\bullet}$) radicals generated by laser flash photolysis [23] and determined rather fast H abstraction: $CumO^{\bullet} + R\text{-}CH_2NR'_2 \rightarrow CumOH + R\text{-}(^{\bullet}CH)NR'_2$. For example, second order rate constant for $CumO^{\bullet}$ reacting with trimethylamine (as representative for the whole series of studied amines in [23]) is $1.6 \times 10^8 M^{-1}s^{-1}$, giving an additional explanation of chain breaking activity of **F-DMA** as a source of H atom from methylene sites. However, activity of C_{60}, C_{60}-Py and **F-DMA** is almost the same (see Table 2), thus, we suppose that H atom abstraction has rather small contribution and overall antioxidant activity of **F-DMA** is due to addition of alkyl radicals to C_{60} core. Moreover, dimethylamine group or pirrolidine ring cannot be an efficient donor of H atom for peroxyl radicals, because H abstraction from aliphatic and alicyclic amines is a relatively slow process (k = 47.5 $M^{-1}s^{-1}$ and 2.6 $M^{-1}s^{-1}$ for reaction of *t*-butylperoxyl radical with pirrolidine and piperidine, respectively, as we found in *Landoldt-Borstein* data [24]). We exclude this kind of antioxidant activity of **F-DMA** and such assumption was verified by the results of our measurements of the rate of peroxidation of cumene in solution, as model process mediated by peroxyl (cumylperoxyl) radicals at 30°C. Enes and coworkers reported [11] that pristine C_{60} fullerene does not trap peroxyl radicals with the rate that is sufficient to stop the propagation chain, therefore, we predicted that **F-DMA** also will not cause any significant inhibition effect. Indeed, we did not observed neither inhibition nor retardation, as the rate of uninhibited peroxidation of cumene (R_{ox} = 3.0×10^{-7} Ms^{-1}) is almost the same as R_{ox} = 2.6×10^{-7} Ms^{-1} determined for cumene containing 14.4 μM **F-DMA** (we also observed the same lack of effect for other concentrations of **F-DMA**, from 4 to 15 μM). Therefore, neither C_{60} nor methyl/methylene groups react with peroxyls in kinetically significant rate.

In conclusion, the fullerene containing covalently bonded *N*,*N*-dimethylaniline via pyrrolidine ring exhibits antioxidant activity during high temperature oxidation of stearic acid as a model of saturated hydrocarbon while the same compound is not active at low temperature during peroxidation of cumene. The plausible explanation of such behaviour is that **F-DMA** is a chain-breaking antioxidant able to trap alkoxyl and alkyl radicals that are responsible for propagation process at high temperature oxidation of hydrocarbons.

Acknowledgments. *The authors gratefully acknowledge financial support from the National Science Centre of Poland (NCN grant No. 2014/15/B/ST4/04835).*

REFERENCES

1. R. Amorati; L. Valgimigli. *Free Radical Res.*, **49**, 633 (2015).
2. G. Gryn'ova; J. L. Hodgson; M. L. Coote. *Org. Biomol. Chem.*, **9**, 480 (2011).
3. R. Lee; G. Gryn'ova; K. U. Ingold; M. L. Coote. *Phys. Chem. Chem. Phys.*, **18**, 23673 (2016).

4. L. M. Smith; H. M. Aitken; M. L. Coote. *Acc. Chem. Res.*, **51**, 2006 (2018).
5. M. C. Foti; R. Amorati. *J. Pharm. Pharmacol.*, **61**, 1435 (2009).
6. P. J. Krusic; E. Wasserman; P. N. Keizer; J. R. Morton; K. F. Preston. *Science*, **254**, 1183 (1991).
7. R. Klemt; E. Roduner; H. Fischer. *Chem. Phys. Lett.*, **229**, 524 (1994).
8. E. Schaffner; H. Fischer. *J. Phys. Chem.*, **97**, 13149 (1993).
9. M. Walbiner; H. Fischer. *J. Phys. Chem.*, **97**, 4880 (1993).
10. J. R. Morton; F. Negri; K. F. Preston. *Acc. Chem. Res.*, **31**, 63 (1998).
11. R. F. Enes; A. C. Tomé; J. A. S. Cavaleiro; R. Amorati; M. G. Fumo; G. F. Pedulli; L. Valgimigli. *Chem. Eur. J.*, **12**, 4646 (2006).
12. R. Czochara; P. Ziaja; P. Piotrowski; R. Pokrop; G. Litwinienko. *Carbon*, **50**, 3943 (2012).
13. R. Czochara; J. Kusio; M. Symonowicz; G. Litwinienko. *Ind. Eng. Chem. Res.*, **55**, 9887 (2016).
14. R. Czochara; J. Kusio; G. Litwinienko. *RSC Advances*, **7**, 44021 (2017).
15. R. Czochara; M. Grajda; J. Kusio; G. Litwinienko. *Bulg. Chem. Commun.*, **50**, 268 (2018).
16. J. Cedrowski; G. Litwinienko; A. Baschieri; R. Amorati. *Chem. Eur. J.*, **22**, 16441 (2016).
17. G. Litwinienko; A. Daniluk; T. Kasprzycka-Guttman. *Ind. Eng. Chem. Res.*, **39**, 7 (2000).
18. G. Litwinienko, *Analysis of lipid oxidation by Differential Scanning Calorimetry*.in: *Analysis of Lipid Oxidation*, Kamal-Eldin A., Pokorny J. Eds., pp. 152-193AOCS Publishing, Champaign, IL, 2005.
19. K. Jodko-Piórecka; J. Cędrowski; G. Litwinienko, in: *Measurement of Antioxidant Activity and Capacity: Recent Trends and Applications*; Apak, R., Capanoglu, E., Shahidi, F., Eds.; John Wiley and Sons Ltd., Chichester UK, 2018.
20. Le Harris; H. S. Olcott. *J. Am. Oil Chem. Soc.*, **43**, 11 (1966).
21. G. M. Coppinger; J. D. Swalen. *J. Am. Chem. Soc*., **83**, 4900 (1961).
22. E. Baciocchi; A. Calcagni; O. Lanzalunga. *J. Org. Chem.*, **73**, 4110 (2008).
23. M. Salamone; G. A. DiLabio; M. Bietti. *J. Org Chem.*, **76**, 6264 (2011).
24. J. A. Howard, J. C. Scaiano, *Oxyl-, Peroxyl- and Related Radicals* in *Landoldt-Borstein New Series*, Vol. 13, *Radical Reaction Rates in Luiquids*, H. Fischer Ed., subvolume d, chapt. 8, page 375, Springer-Verlag, Berlin-Heidelberg, 1984.